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HYDROCOOLING STACKED CRATES OF CELERY AND SWEET CORN

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CONTENTS

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The work was conducted under the supervision of Earl K. Bowman, and Joseph F. Herrick, Transportation and Facilities Research Division, Agricultural Research Service, U.S. Department of Agriculture.

SUMMARY

Hydrocooling tests of celery and sweet corn in stacks of 32 and 40 crates were made to determine the feasibility of a system of handling and hydrocooling these products in unit loads. In a pilot plant hydrocooling room, stacks of crates were hydrocooled with 38° F. refrigerated water sprayed from overhead nozzles. Laboratory studies were also made to determine heat transfer characteristics.

In pilot plant tests, celery in crates stacked four layers high with eight crates in each layer was cooled from 75° to 47.2° F. in 35.4 minutes at a waterflow rate of 63.2 g.p.m. This time compares favorably with the time required to cool celery in present flood-type hydrocoolers, in which crates are placed in single layers. Spray nozzles in the pilot plant precooler were mounted 105 inches above the floor (34 inches above the stacks of celery).

Sweet corn, in crates stacked five layers high and eight crates to a layer, cooled very slowly in the pilot plant hydrocooling room. At a waterflow rate of 91.2 g.p.m., sweet corn temperature was reduced from 90° to 44.5° F. in 3-1/3 hours. In conventional hydrocoolers, sweet corn temperature can be reduced from 90° to 44.5° F. in 1-1/3 hours. Results of laboratory tests, however, indicate that if 38° F. refrigerated water can be sprayed onto corn in sufficient amounts, its temperature should be reduced from 90° to 45° F. in 1 hour. The time required for this temperature reduction in preliminary tests of corn piled in bulk in pallet boxes and cooled in the pilot plant hydrocooling room was about 1-1/2 hours. Reduction of this time is possible by improved arrangement of the pallet boxes in relation to the water spray from the shower nozzles.

In a system of unit load handling of celery and sweet corn, mechanical handling equipment would be used to move stacks of crates from field trucks into the precooling room and then into the shipping vehicle. The main advantages of this system are the elimination of manual crate handling and minimum rehandling. Other advantages include reduced crate breakage and improved produce quality maintenance through provision of temporary cold storage without the necessity of moving the produce before loading it for shipment.

HYDROCOOLING STACKED CRATES OF CELERY AND SWEET CORN

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INTRODUCTION

During the 1962-63 celery and corn season, Florida growers shipped 7,505,000 crates of celery and 8,804,000 crates of sweet corn.[1] Production of both crops was 5 percent higher than during the previous year.

Many growers produce both celery and sweet corn. The crops are harvested and packed similarly and both are precooled before shipment. Sweet corn and celery are harvested and packed in crates in the field on a mobile packing vehicle commonly referred to as a mule train. Precooling is usually done in hydrocooling tunnels under a shower of refrigerated water.

The individual crates are manually handled several times between packing and shipping.

In the field, workers stack the crates on trucks towed behind the mule trains. At the precooling plant, workers pick up crates from the trucks and toss them onto an extendable roller or belt conveyor (fig. 1). Chain conveyors transport the crates to temporary storage. Workers stationed alongside the conveyor set the crates on the floor in three-high stacks of celery or five-high stacks of sweet corn (fig. 2).

When orders are received for a load of produce, workers pick up the crates and set them on a chain conveyor that transports them to the hydrocooler. At the input end of the hydrocooler, a worker pulls crates from the chain conveyor and slides them on a metal chute into the hydrocooling tunnel (fig. 3). At the output end of the hydrocooler, workers pull crates onto another chain conveyor (fig. 4) that transports them to a crew of workers on the dock who load them into railroad cars or semitrailer trucks.

The hydrocooling tunnels are about 47 feet long and consist of one to three lanes, each 6 feet wide. Conveyors equipped with adjustable speed motors, which are timed to keep each crate of produce under a shower of refrigerated water for 15 to 20 minutes, transport the packed crates through the hydrocooler (fig. 5).

Since the present system of handling and hydrocooling does not provide much flexibility and requires considerable rehandling of crates, a new system was envisioned whereby the crates would be handled and hydrocooled in unit loads. Stacks of 32 crates of celery or 40 crates of corn would be unloaded from the field truck with forklift trucks and set into a combined storage-precooling room at the plant. In this room, water would be showered onto the stacks from overhead water nozzles. With this system, manual crate handling would be eliminated and rehandling minimized.

In addition to reduced labor requirements and costs, other advantages of the unit load system would be reduced crate breakage and improvement of produce quality maintenance through provision of temporary cold storage without the necessity of moving the produce. In present precooling facilities, produce may be stored for several hours in an unrefrigerated area before it

[1] Florida Department of Agriculture. Florida Agricultural Statistics, Vegetable Summary, 123 pp., 1963.

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Figure 1.--Unloading celery from a field truck at the precooling plant.

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Figure 2.--Floor storage in a precooling plant. Celery in left background and corn in right foreground.

Figure 3.--Loading hydro-cooling tunnel with crates of celery.

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Figure 4.--Pulling crates of celery from the hydro-cooling tunnel onto a chain conveyor.

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BN 26902

Figure 5.--Shower of water cascading over cooling coils and showering onto packed produce.

is cooled. In the combined storage-precooling room, the produce would be cooled as soon as it is brought from the field and recooled later if necessary, simply by turning on a water valve.

A pilot plant hydrocooling room was constructed by a Florida celery and sweet corn grower. Studies were made by U.S. Department of Agriculture researchers to determine if precooling of celery and sweet corn in crates in unit loads was feasible.

Tests were conducted in the pilot plant hydrocooling room to determine cooling rates of packed celery and sweet corn in unit loads, and laboratory studies were made of heat transfer characteristics of celery and sweet corn to establish cooling standards to aid in evaluation of the hydrocooler.

THE PILOT PLANT FACILITY

The pilot plant hydrocooling room was an area large enough to accommodate 22 stacks of crates and to allow sufficient maneuvering room for industrial lift trucks. The stacks were 45 by 48-3/4 inches and 66 to 71 inches high.

Shower nozzles were installed one nozzle to a stack, 105 inches above the floor. The nozzles sprayed water in a fullcone spray pattern that distributes water uniformly. The nozzle construction included internal offset vanes to give good water dispersion. A nozzle with a 1-1/2-inch pipe connection and an orifice diameter of 23/32 inch was used. This nozzle is designed to pass a maximum size particle of 13/32 inch and to deliver 35.5 gallons of water per minute at 10 p.s.i. pressure.

After initial hydrocooling runs were made, extra nozzles were added to some stack positions to increase the amount of water sprayed onto the stack to allow comparison of different waterflow rates. Two nozzles sprayed 63.2 gallons of water per minute and three nozzles sprayed 91.2 gallons of water per minute onto each stack. The three waterflow rates are equivalent to 2-1/3, 4-1/4, and 6 gallons of water per square foot of stack area per minute, respectively.

The temperature of the water used in all pilot plant tests was approximately 38° F.

A 3,000-pound-capacity lift truck, which was equipped with a hydraulic clamp to pick up stacks, was used to set stacks under the overhead shower nozzles in the room (fig. 6).

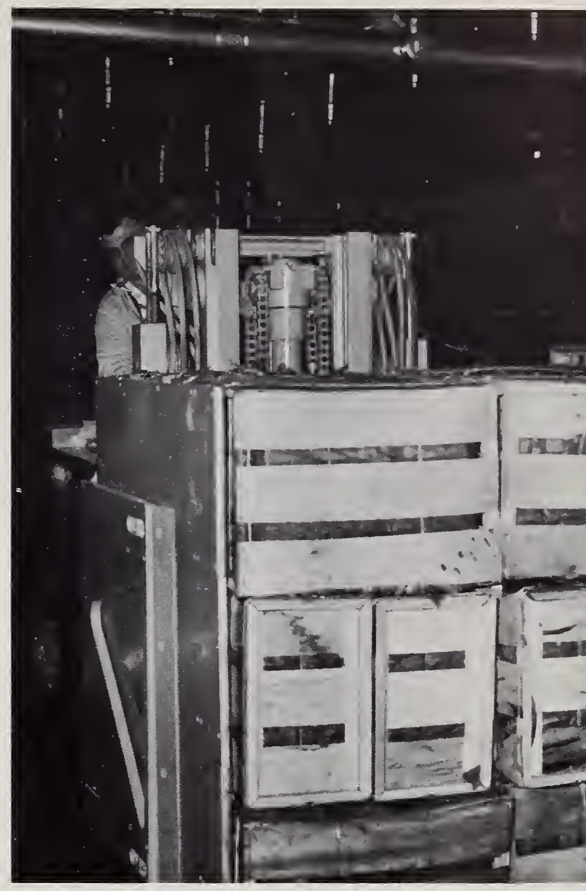

Figure 6.--Industrial lift truck with clamps setting a crate stack under an overhead shower nozzle.

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CELERY

Pilot Plant Studies

Test Procedures

Celery crates were stacked in the room in loads of 32 crates. The crates were stacked in a block pattern with four layers of eight crates per course. Each stack weighed approximately 2,200 pounds and was 71 inches high. The wirebound crate in which celery is packed is 22 by 16-1/4 by 12-1/4 inches. The crates were stacked with the 16-1/4-inch side vertical; in this position, the celery stalks are also vertical, in alternate rows of butt up and butt down.

The temperature of the celery at the beginning of all the cooling tests was approximately 75° F. Temperature of the celery during the tests was measured by copper-constantan thermocouple junctions and a recording potentiometer. The 20-point recording potentiometer recorded every half minute the temperature of one of 10 thermocouples. The temperature of each thermocouple was recorded at 5-minute intervals.

Cooling performance is often evaluated by determining and comparing cooling coefficients. In this report, half-cooling time was used as the performance factor for evaluating the cooling process. As the name implies, half-cooling time represents the time required to cool the product to one-half the initial temperature difference between the product and the cooling fluid.

Half-cooling time is a convenient measure because it approximates the time needed to remove one-half the field heat that is to be taken from the commodity. Two half-cooling times are needed to remove three-quarters of the field heat from the product and three half-cooling times are needed to remove 7/8 of the field heat (fig. 7). [2]

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[2] Sainsbury, G. F. Cooling Apples and Pears in Storage Rooms. U.S. Dept. Agr. Mktg. Res. Rpt. No. 474, 55 pp., illus. 1961.

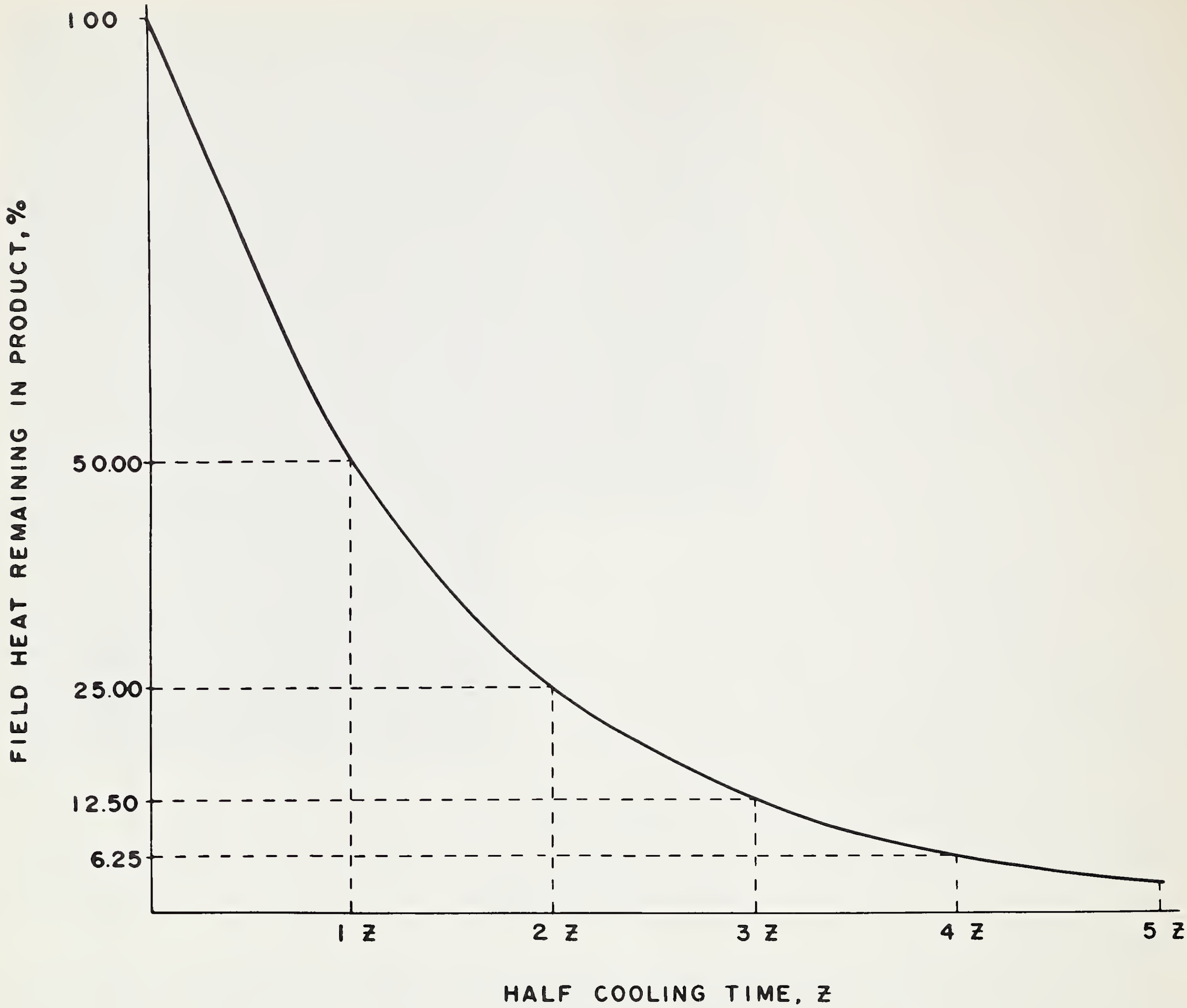

Figure 7.--Relations between field heat and half-cooling time.

All values of half-cooling time were calculated from the cooling coefficient determined for each thermocouple location. The cooling coefficient is the rate of cooling divided by the temperature difference between the object and the cooling fluid.[3] Cooling coefficients for a period in question were calculated on the basis of the logarithmic mean temperature difference between the object and cooling water and the initial temperature difference between the object and the cooling water. Those cooling coefficients pertaining to similar thermocouple locations in each test were averaged and these values were converted to half-cooling times. (See appendix for example of procedure.)

Half-cooling times of celery in crates in unit loads were determined in three tests. Thermocouples were inserted into celery stalks in the center of the heavy butt portion, in the surface of the outer rib, and in the petioles of the stalks. Specimen stalks were packed in wirebound crates and the crates were placed in each of the four layers of the stacks.

An extra thermocouple was wired to the top of the stack to record the temperature of the water.

[3] Guillou, Rene. Coolers for Fruits and Vegetables. Calif. Agr. Expt. Sta. Bul. No. 773, 65 pp., illus. 1960.

In the first test, nine thermocouples were inserted into one crate, and the crate was set in the bottom layer of the stack of crates. In the second test, three thermocouples were placed in each of three crates. One crate was placed in the bottom layer of the stack, the second crate was placed in the third layer of the stack and the third crate was placed in the top layer of the stack. In the third test, two thermocouples were placed in each of four crates and one crate was then set in each of the four layers of the stack.

As a final test on cooling performance, a wirebound crate was modified so that the space through which water could enter the crate was enlarged. The modified crate has 57.75 square inches of space between the wood veneer slats on the side of the crate exposed to the water spray. The standard wirebound crate has 28.9 square inches of space between these slats.

Two replications were made to compare cooling performance of the standard and modified crates. These crates were not placed in stacks, but were approximately 24 inches below a water nozzle.

Thermocouple locations in celery in the standard and modified crates are shown in figure 8. Thermocouples were on the outer surfaces of the celery petioles, in the butt of the stalk (1 inch from the base), and in the heart of the stalk (2-1/2 inches from the base).

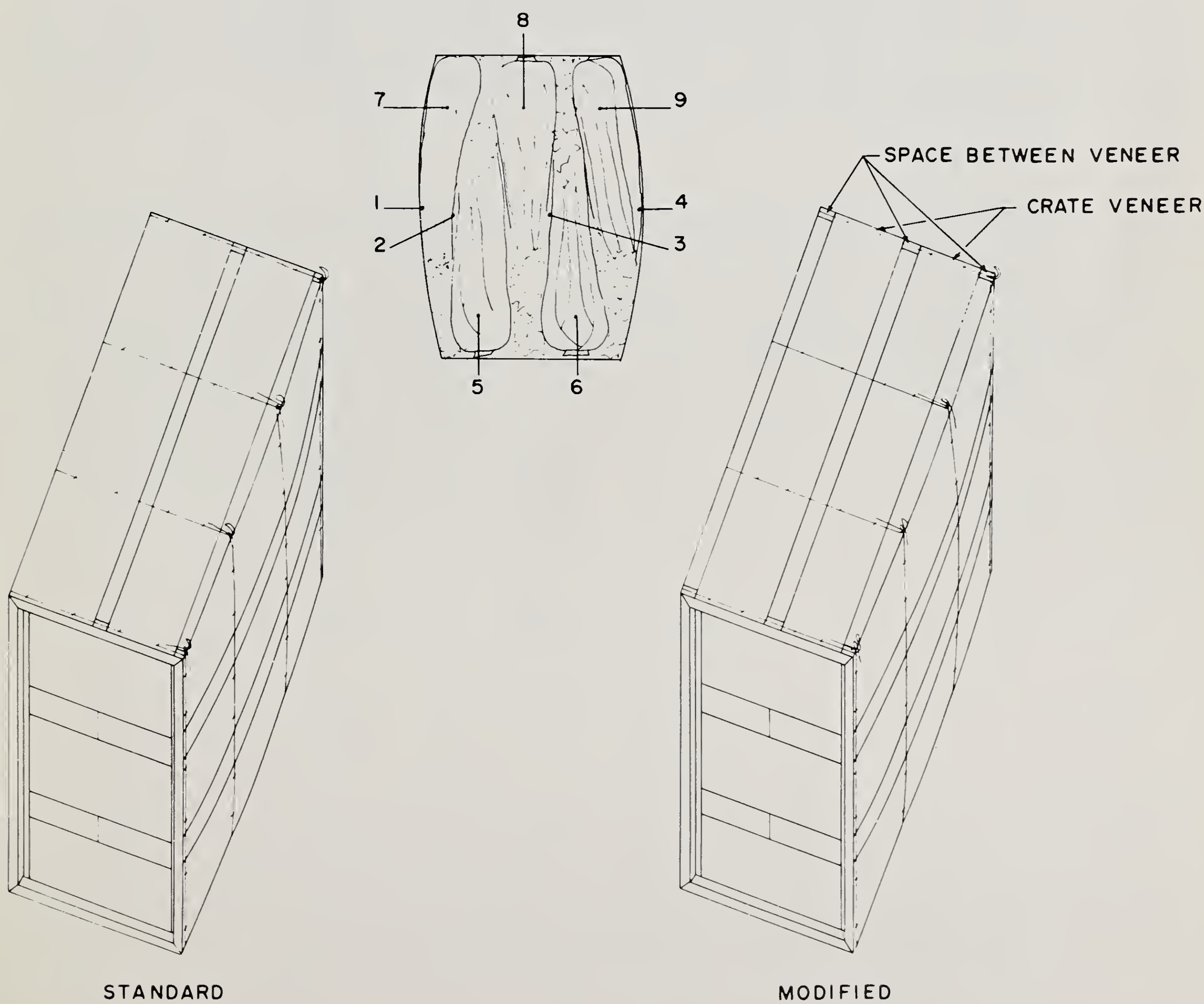

Figure 8.--Sketch of modified and standard wirebound celery crates. Thermocouple positions in celery stalks are: 1 to 4, petioles; 5 and 6, butts (1 inch deep into base of stalk); 7 to 9, hearts (2-1/2 inches deep into base of stalk).

Because of the time lag for temperature within the object to be affected by surface temperature, average cooling coefficient values for celery were computed only during certain periods of the cooling cycle. This provides a common basis for comparison. The time period for celery petioles over which cooling coefficients were averaged was 5 to 20 minutes. The time period for the celery butt was from 10 to 45 minutes after the start of the cooling period.

Results

Unit loads.--Half-cooling times for celery butts in the top and third layer crates of the stack were approximately the same at each of the three waterflow rates (table 1). However, cooling in the second and especially the bottom layer crates was significantly slower at the 35.5 g.p.m. rate. There was very little difference in cooling rate between the two higher waterflow rates in the second and bottom layer crates in the stack.

At 35.5 gallons per minute, a total of 2,400 gallons of water and 67.6 minutes were required to cool a stack of 32 crates of celery from 75° to 47.2° F.[4] At 63.2 g.p.m., 35.4 minutes and 2,237 gallons of water were needed, and at 91.2 g.p.m., 44.4 minutes and 4,049 gallons of water were needed to cool celery from 75° F. to 47.2° F. when sprayed with 38° F. water.

Three water nozzles were used to obtain a flow of 91.2 g.p.m. in the pilot plant experiment. Inefficiencies thus introduced may have been contributing factors to slightly increasing the time needed to cool celery. Another factor may have been the narrow opening between crate slats, which restricted the amount of water that could pass through the top crate and thus limited the amount of water available to cool lower crates in the stack.

Table 1.--Hydrocooling celery packed in wirebound crates and stacked in unit loads of 32 crates, pilot plant tests: Half-cooling times for butts, three waterflow rates[1]

Location of crate in 4-high stack and orientation of stalk in crate	35.5 g.p.m.	63.2 g.p.m.	91.2 g.p.m.
	Minutes	Minutes	Minutes
Top layer:			
Butt down	12.6	10.9	14.9
Butt up	11.9	12.1	14.3
3d layer:			
Butt down	17.2	17.6	10.3
Butt up	22.9	15.1	17.3
2d layer:			
Butt down	22.8	10.5	9.4
Butt up	20.2	13.2	14.8
Bottom layer:			
Butt down	26.7	17.7	22.2
Butt up	33.8	15.1	20.2

[1] Thermocouple inserted 1-inch deep into base of stalk.

[4] Two half-cooling times are needed to reduce temperatures from 75° to 47.2° F. At the end of one half-cooling time the temperature will be 56.5° F.

Representative cooling curves for celery butts packed in the top and bottom crates of a four-crate-high stack are shown in figure 9. The cooling rate of celery in these tests was dependent on the orientation of the stalk in the crate, the location of the crate in the stack, and the waterflow rate.

The orientation of the stalk within the crate had a noticeable effect on the rate of cooling. Stalks with the butt end up tended to cool at a slower rate than stalks with butts at the bottom of the crate.

Celery stalks in crates in lower layers of the stack did not cool as rapidly as celery in crates in the top layer of the stack. This effect is due to the channeling of water through the crates and thus through the stacks.

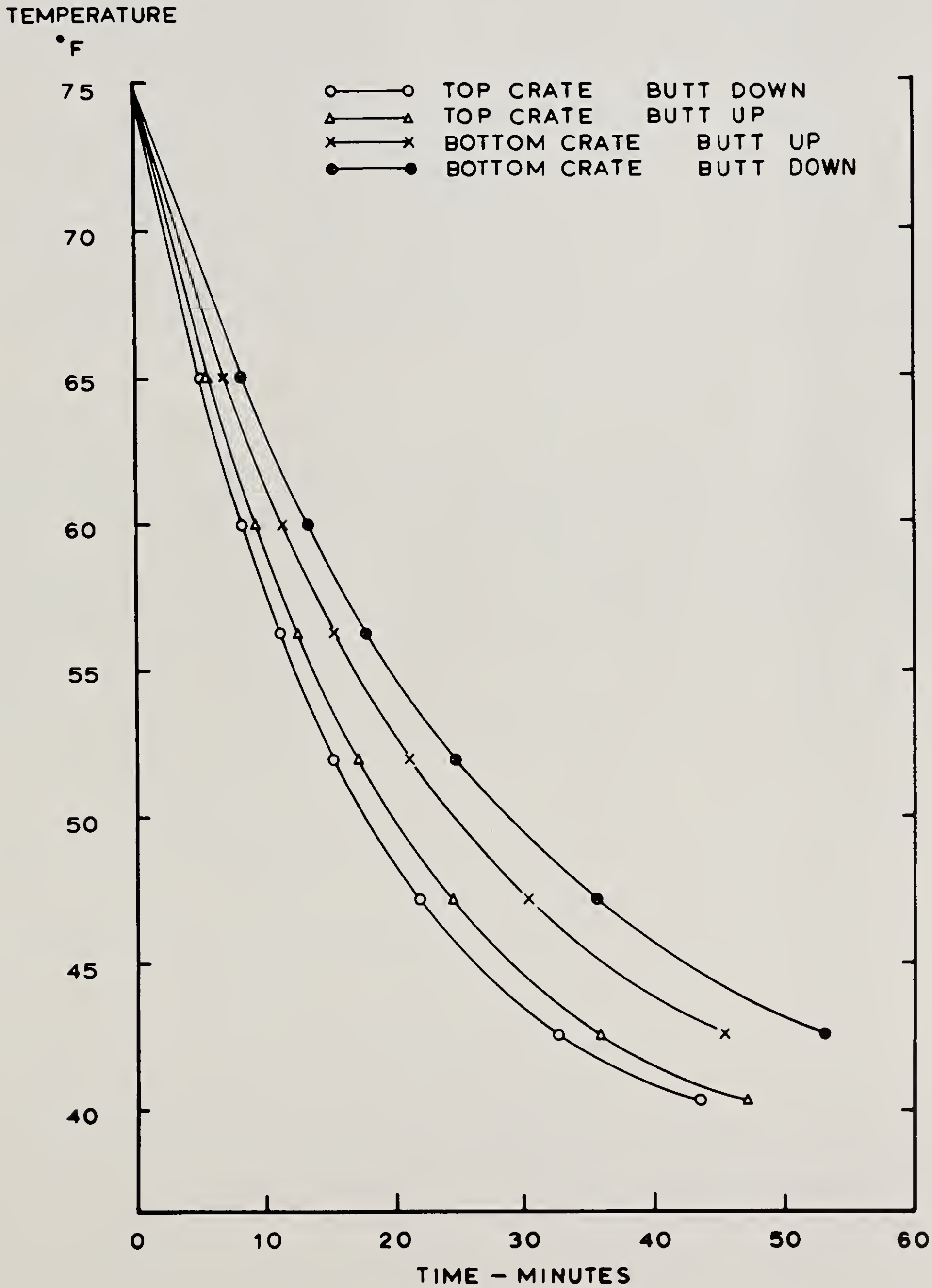

Figure 9.--Cooling curves for celery butts packed in the top and bottom crates of a stack four crates high, waterflow rate 63.2 g.p.m.

The base of the stalk (including the butt and heart as defined in this report) is the slowest part of the stalk to cool. It has the most mass and the greatest density. Therefore, there is a low rate of heat conductance from the center of the base to the outer surface. Water tends to channel and come into contact with only a portion of the surface, resulting in reduced capacity for heat convection from the surface to the refrigerated water. This can be partially alleviated by spraying additional amounts of water onto the stack. At higher flow rates, however, half-cooling time is not reduced beyond a certain point because of the water shedding effect of the wood veneer slats on the upper side of the crate.

Modified crate.--Hydrocooling was more effective when the openings between the slats of the wirebound crate were enlarged (table 2). Half-cooling times for nearly all points on the celery stalks were reduced one-half or more. However, there were some points on the stalks that did not cool any faster in the modified crate than in the standard crate.

The stalk heart (thermocouple positions 7, 8, and 9 in table 2) was the slowest part of the stalk to cool. Half-cooling time for hearts was 15 to 25 minutes, compared to 9 to 12 minutes for butts. The temperature of celery butts was measured at the bottom of the crate, and the temperature of celery hearts was measured at the top of the crate (fig. 8).

Cooling curves for celery hearts in the standard and modified crates are shown in figure 10.

Because of the construction of the celery stalk, the heart of the stalk is the slowest part to cool when the stalk is packed with butt upright; the outer ribs join the base of the stalk in an overlapping configuration and shed water. When the stalk is packed with the butt down, water flows down the petioles and to the heart of the stalk. Therefore, the heart of a celery stalk packed with butt end down cools at a faster rate than the heart of a stalk packed with the butt upright.

Table 2.--Hydrocooling celery packed in standard and modified wirebound crates, pilot plant tests: Half-cooling times for butts, hearts, and petioles

Stalk part and thermocouple position (fig. 8)	Standard crate	Modified crate
	Minutes	Minutes
Butt, butt down:[1]		
5	19.7	8.7
6	11.9	12.4
Heart, butt up:[2]		
7	68.8	24.7
8	27.6	20.8
9	30.7	14.7
Petioles:[3]		
1	19.8	3.9
2	42.1	5.2
3	3.8	7.4
4	1.9	1.0

[1] Thermocouple inserted 1 inch into base of stalk.
[2] Thermocouple inserted 2-1/2 inches into base of stalk.
[3] Thermocouple just below surface of petiole.

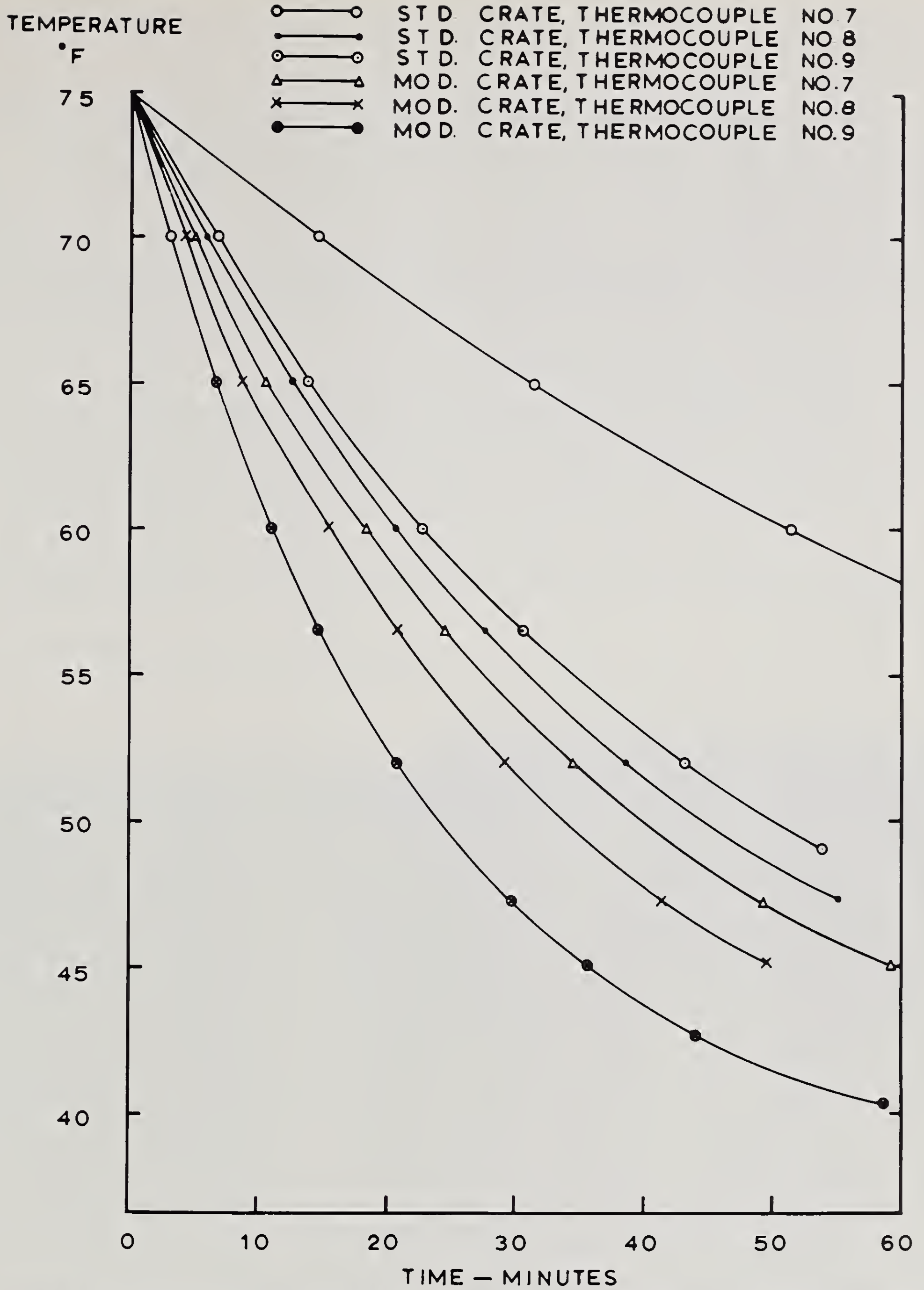

Figure 10.--Cooling curves for celery hearts packed in standard and modified crates.

Laboratory Studies

Test Procedures

A small-scale laboratory hydrocooler permitted hydrocooling tests to be run on small lots of celery. The small hydrocooler was designed to give close control of waterflow rates and water temperatures and immediate replication of test runs under very closely controlled conditions.

The hydrocooler test chamber was designed and constructed to simulate the cooling method employed by the pilot plant unit-load hydrocooler. Spray nozzles provided uniform distribution at varying waterflow rates. The nozzles had a full-cone spray pattern similar to the nozzles used in the pilot studies.

Four low-pressure spray nozzles were installed in the top of the hydrocooler chamber to give uniform spray coverage at flow rates varying from 4 to 12 gallons per minute. Waterflow was measured with a bellows-type, pressure differential, recording flowmeter.

Water temperature was held as constant as possible. It averaged 35.3° F. with a range of 33.5° to 39.25° F. in all tests.

The temperature of the celery stalks was recorded during the cooling process by a 16-point recording potentiometer. The temperature of each thermocouple was recorded every 4 minutes. Thermocouples were constructed of 36 A.W.G. copper and constantan wire with fused junctions. The junctions were inserted into the produce.

Four celery hydrocooling tests were run in the laboratory hydrocooler. The first test determined the ideal cooling curve for celery packed in a wiremesh basket. The second test determined the ideal cooling curve for a single stalk of celery fully exposed to the spray from four full-cone spray nozzles. The third test determined the effect of celery size on the cooling curve for celery packed in the wiremesh basket. Celery size is determined by the number of dozens of stalks that can be packed in a crate. Celery sizes usually packed in Florida are 2, 2-1/2, 3, 4, 6, and 8. The fourth test obtained comparative cooling curves for celery packed in standard and modified wirebound shipping crates.

In the first test, celery was packed in a 12- by 12- by 10-inch wiremesh basket. Twelve size 2 stalks were packed in the basket in alternating layers of butt up and butt down (fig. 11).

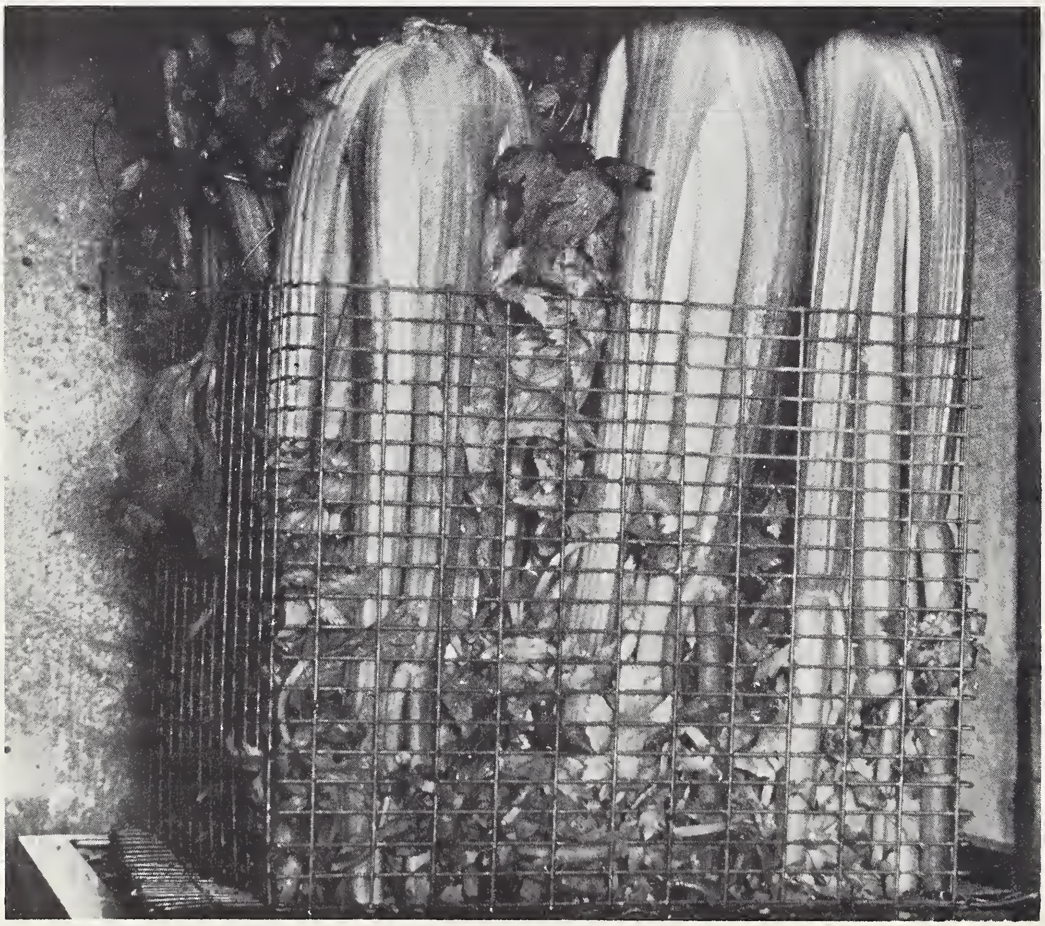

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Figure 11.--Celery stalks packed in a 12- by 12- by 10-inch wiremesh basket.

Thermocouples were placed in the two center stalks in the basket. One center stalk was packed butt up and the other center stalk was packed butt down. Thermocouples were inserted in the base of the stalk, on the surface of the base, and on the surfaces of the petioles at the mid-length and top of the stalk. Waterflow rates of 4, 8, and 12 g.p.m. were tested.

In the second test (single stalks of celery), three waterflow rates were tested: 6, 8, and 10 g.p.m. In these tests, a single stalk of size 3 celery was wired in an upright position and completely exposed to the spray from four full-cone spray nozzles (fig. 12). In addition, a size 2 stalk was cooled at 8 g.p.m. Thermocouples were placed 1 inch from the butt into the center of the stalk, on the outer surface of the base and on outer surfaces of petioles (2-1/2, 7-1/2, and 14 inches from the stalk butt). Another thermocouple was inserted into the heart of the stalk, 2-1/2 inches from the base.

In the third test (celery packed in a wiremesh basket), the waterflow rate was 6 g.p.m. and celery sizes 2, 3, 4, and 6 were tested. In the tests, 12 size 2 stalks, 20 size 3 stalks, 25 size 4 stalks, or 36 size 6 stalks were packed in the basket. Only one size of celery was cooled in each cooling run. Temperatures were recorded in the base of the stalk 1 inch from the butt, in the heart of the stalk 2-1/2 inches from the butt, and in the outer surfaces of the base and petioles.

The fourth test compared cooling curves for celery packed in standard wirebound shipping crates and celery packed in a crate in which the veneer slats were reduced 1 inch in width from

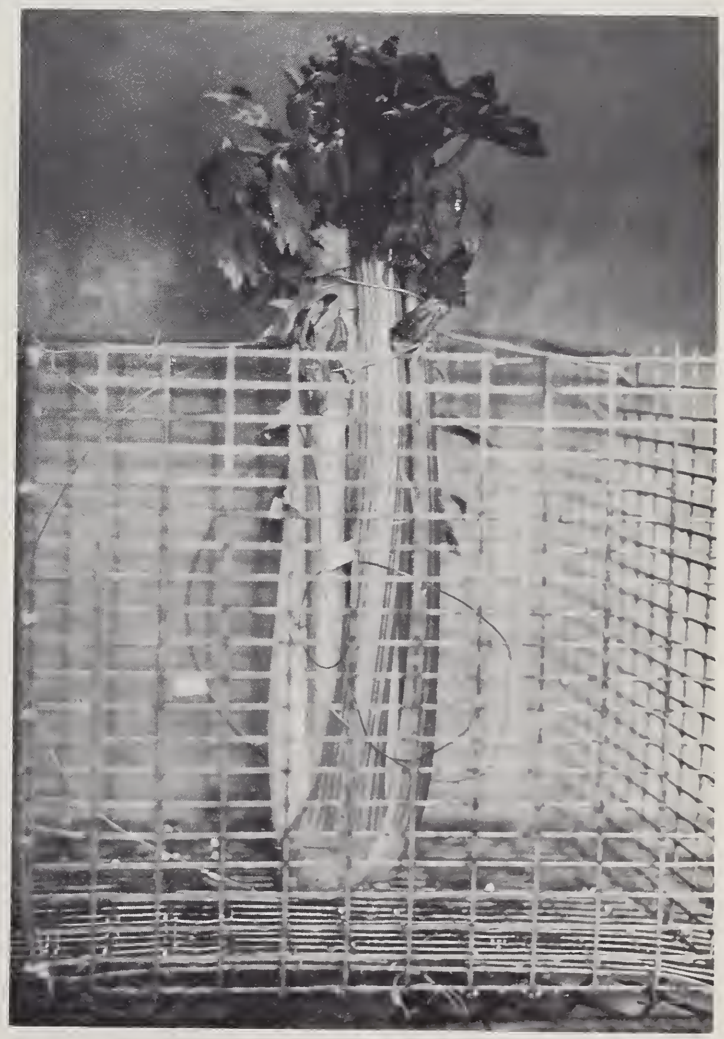

Figure 12.--A single stalk of celery wired in an upright position for cooling test.

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the standard size.[5] Waterflow rate for this test was 6 g.p.m. Thermocouples were placed in the base of the stalks 1 inch from the butt, in the heart of the stalks 2-1/2 inches from the butt, and in the petioles 7-1/2 inches from the stalk butt (fig. 13).

Half-cooling times were determined from calculated cooling coefficients for each thermocouple location for each test. Cooling coefficients calculated for the first few minutes of the cooling cycle were not included in the cooling coefficient average because of the time lag for a temperature change to become fully established from the outside to the inside of the celery.

The time period over which cooling coefficients were averaged, for celery butts and hearts that were packed in a wiremesh basket, was from 11 minutes to 32 minutes after the start of the cooling cycle. Cooling coefficients for outer surfaces and petioles were calculated from the beginning of the cooling cycle until 15 minutes after the start.

Cooling coefficients for stalk hearts that were packed butt down in the basket were averaged from the start of the cooling period until 13 minutes after the start. By the end of approximately 15 minutes, the heart temperature had reached water temperature.

The rate of cooling was faster and the time lag was less with single stalks than with stalks packed in a basket. Cooling coefficients for single celery butts and hearts oriented butt upright were calculated and averaged for the time period from 7 to 28 minutes after the start of the cooling period. For celery hearts oriented butt down, and for all butt and petiole surfaces, the cooling coefficients were calculated from the beginning of the cooling cycle until 13 minutes after the start of the cooling cycle.

Cooling coefficients for celery butts and hearts packed in wirebound crates were averaged for the period between 10 and 50 minutes after the start of cooling. Petiole cooling coefficients were averaged over a 15-minute period beginning 5 minutes after start of cooling.

Results

Wiremesh baskets, three waterflow rates.--Half-cooling times and cooling curves for celery hydrocooled in a wiremesh basket are shown in table 3 and figure 14. Cooling curves in figures 14, 15, 16, and 19 are based on temperature ratios; this is the ratio of the difference in the temperature of the product and the water at any time during cooling to the initial difference in temperature between the product and the water. (See equation IV in appendix.) Celery butts definitely cooled faster when the butt was packed downward (fig. 14A). However, when the waterflow rate was increased, butts packed in the upward position cooled nearly as fast as butts packed in the downward position (fig. 14B).

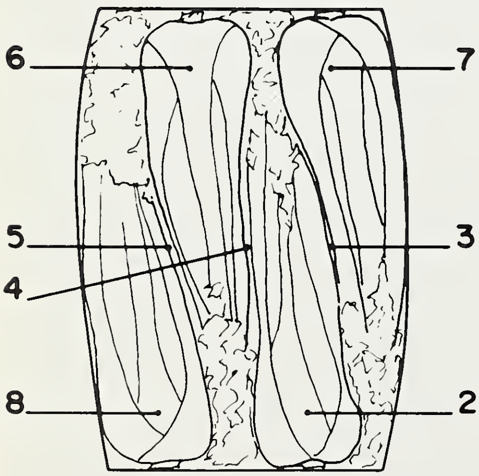

Figure 13.--Thermocouple positions in celery stalks in laboratory tests of standard and modified crates: 2 and 8, butt (1 inch deep in stalk); 6 and 7, heart (2-1/2 inches deep in stalk); 3, 4, and 5, surface of petiole (7-1/2 inches from base of stalk).

[5] This crate was modified in a slightly different way from the one used in the pilot plant tests.

The path of waterflow over the stalk had a noticeable effect on the half-cooling time for butt and petiole surfaces. When the stalk was packed in the basket with butt up, the butt surface cooled faster than the surface of the petiole at the mid-length of the stalk (fig. 14C). When the stalk was packed butt down, the celery petiole still cooled more slowly than the butt surface, but not as slowly as when the stalk was packed butt up. In each cooling test, the half-cooling time for the top of the petiole was less than for any other point on the stalk (fig. 14D).

Single stalks.--In the second series of tests, a single stalk of celery was cooled in each cooling run. A size 3 celery stalk, wired in an upright position, was sprayed with 35° F. water at 6, 8, and 10 gallons of water per minute. Half-cooling times (table 4 and fig. 15A) for celery butts oriented butt down decreased with increased waterflow rates. However, half-cooling time increased with increased waterflow rate for celery butts oriented butt up.

This unexplainable effect appears valid for the particular circumstances. This condition would not normally be expected to occur.

The celery heart cooled much faster than the celery butt when the stalk was oriented butt down (fig. 15B). However, when the stalk was oriented butt up, hearts cooled much more slowly than butts. Moreover, for hearts oriented butt up the half-cooling time increased as waterflow rate increased. As in the case with butt cooling, this effect would not normally be expected and is unexplainable.

As expected, half-cooling time for butt and petiole surfaces decreased with increased waterflow (table 4). Thermocouples that recorded the temperature of the butt surface, heart surface, and inner surface of the petiole 7-1/2 inches from the butt recorded less half-cooling time when the celery stalk was oriented butt down (fig. 15C). In contrast, at the 6 and 8 g.p.m. waterflow rates, the temperature of the outer surface of the petiole 7-1/2 inches from the butt and the inner surface of the petiole 14 inches from the butt reflected less half-cooling time when the celery stalk was packed butt up (table 4).

The trend for petiole surfaces to have less half-cooling time when celery was packed butt up than when it was packed butt down was reversed at the 10 g.p.m. waterflow rate. At the higher flow rate, petiole surfaces cooled faster when celery was oriented butt down.

Table 3.--Hydrocooling size 2 celery packed in wiremesh baskets, laboratory tests: Half-cooling times for butts and petioles, three waterflow rates

Stalk part and orientation of stalk in basket[1]	4 g.p.m.	8 g.p.m.	12 g.p.m.
	Minutes	Minutes	Minutes
Butt: [2]			
Butt down	15.6	12.2	12.6
Butt up	24.0	18.9	13.6
Butt surface:			
Butt down	2.1	1.2	1.0
Butt up	2.0	1.8	1.4
Petiole surface, mid-length of stalk:			
Butt down	--	1.6	1.6
Butt up	--	2.2	4.0
Petiole surface, top of stalk:			
Butt up	1.4	.9	.8

[1] 12 stalks were packed in a 12- x 12- x 10-inch basket.
[2] Thermocouple inserted 1-inch deep into base of stalk.

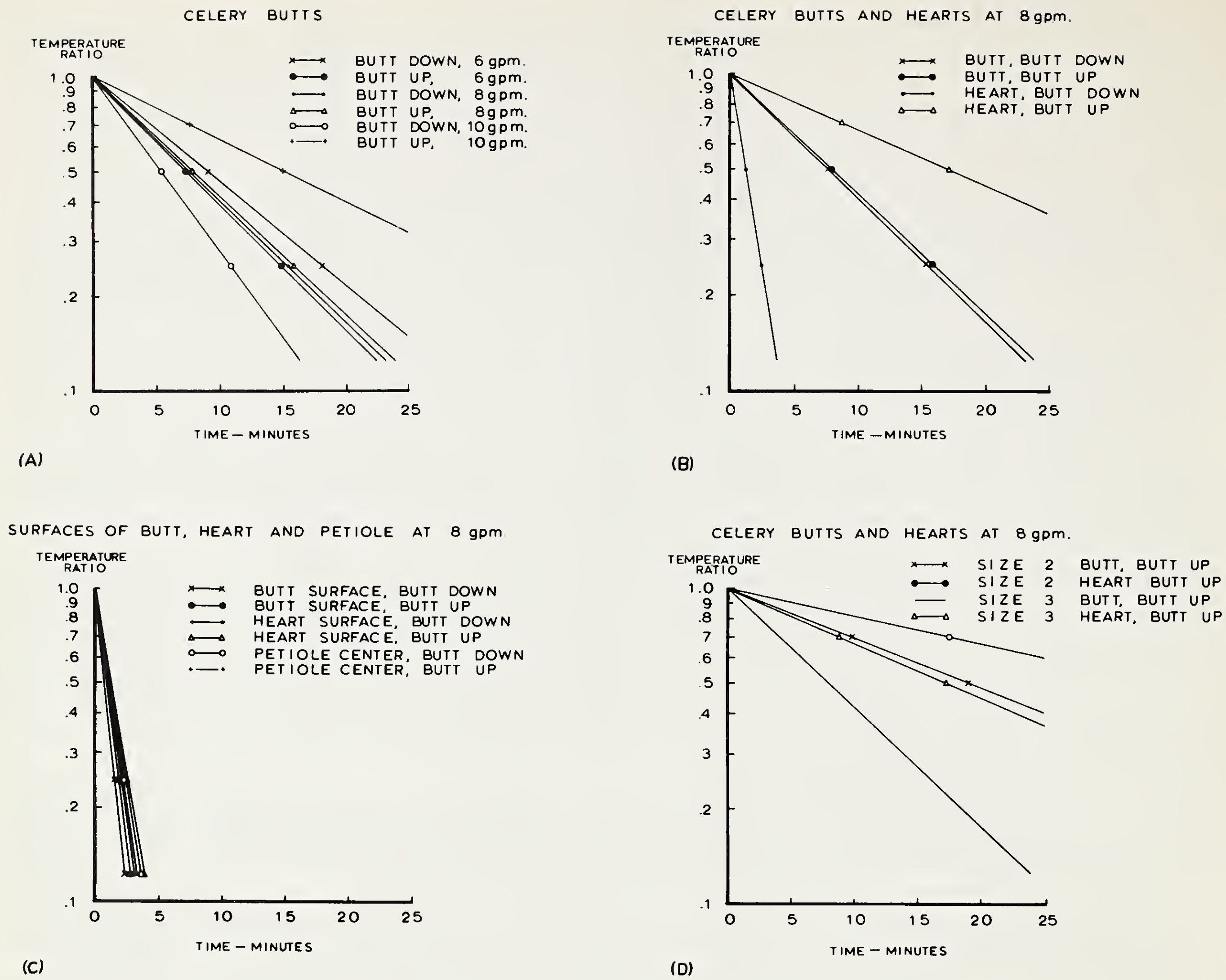

Figure 14.--Cooling curves for celery hydrocooled in a wiremesh basket.

A comparison of cooling rates can be made with size 2 and size 3 celery in table 4. Cooling of the size 2 celery butt and heart was significantly slower than size 3 celery at 8 g.p.m. (fig. 15D). However, half-cooling times for butt, heart, and petiole surfaces for size 2 celery were nearly the same as those for size 3 celery.

Another comparison which can be made is between cooling a single size 2 stalk of celery (table 4) and cooling a basket of size 2 celery (table 3). Half-cooling times for celery butts in both tests were very nearly the same. When the celery butt was packed down, half-cooling time at 8 g.p.m. was 12.2 minutes for stalks in the packed basket and 12.5 minutes for a single stalk of celery. A stalk packed butt up in a basket full of celery had a half-cooling time of 18.9 minutes (table 3) and the half-cooling time for the single celery stalk was also 18.9 minutes (table 4). Some difference was found in half-cooling time for butt surfaces and stalk petioles. In each case, the half-cooling time for the surfaces and for the petioles was less for single stalks than for a number of stalks packed in the wiremesh basket. This shorter half-cooling time

Table 4.--Hydrocooling single stalks of size 2 and 3 celery in wiremesh basket, laboratory tests: Half-cooling times for butts, hearts, and petioles, three waterflow rates

Stalk part and orientation of stalk in basket	Size 3			Size 2
	6 g.p.m.	8 g.p.m.	10 g.p.m.	8 g.p.m.
	Minutes	Minutes	Minutes	Minutes
Butt: [1]				
Butt down	9.1	7.7	5.5	12.5
Butt up	7.5	8.0	15.1	18.9
Heart: [2]				
Butt down	--	1.3	1.2	1.7
Butt up	13.3	17.3	19.6	34.0
Butt surface,[3] 1 inch from base of stalk:				
Butt down	1.0	.8	.8	.7
Butt up	1.1	.9	.9	1.2
Heart surface,[3] 2-1/2 inches from base of stalk:				
Butt down	1.4	1.1	.8	.8
Butt up	1.3	1.2	1.1	1.0
Petiole surface, 7-1/2 inches from base of stalk:				
Butt down	1.4	1.0	.9	1.2
Butt up	2.6	2.2	1.4	1.4
Butt down	1.5	1.2	1.0	.9
Butt up	1.1	1.0	1.1	1.1
Petiole surface, 14 inches from base of stalk:				
Butt down	1.2	1.2	1.0	1.0
Butt up	1.2	1.1	1.2	1.3

[1] Thermocouple inserted 1 inch deep into base of stalk.
[2] Thermocouple inserted 2-1/2 inches deep into base of stalk.
[3] On outer surface of stalk.

is an indication of better waterflow and dispersion over the surfaces of the stalks. Since the single stalk was completely exposed to water spray from the nozzles, this effect is expected.

Wiremesh baskets, four celery sizes.--Half-cooling times for four sizes of celery packed in the wiremesh basket in the third test are shown in table 5. Half-cooling time for celery hearts when size 2 stalks are packed butt up is 62.6 minutes. This time decreases to 31.1 minutes for size 3 celery, and to approximately 15 minutes for sizes 4 and 6 celery. When celery stalks are packed butt up, hearts definitely have longer half-cooling times than any other point in the stalk (fig. 16). However, when celery stalks are packed butt down, hearts cool considerably faster than the butt.

As this test indicates, larger stalks such as size 2 can be expected to cool at slower rates than smaller stalks such as sizes 4 and 6. This slower cooling is due to the greater mass of the butt of the stalk. Note that this will occur even though the petioles of the larger stalks cool as

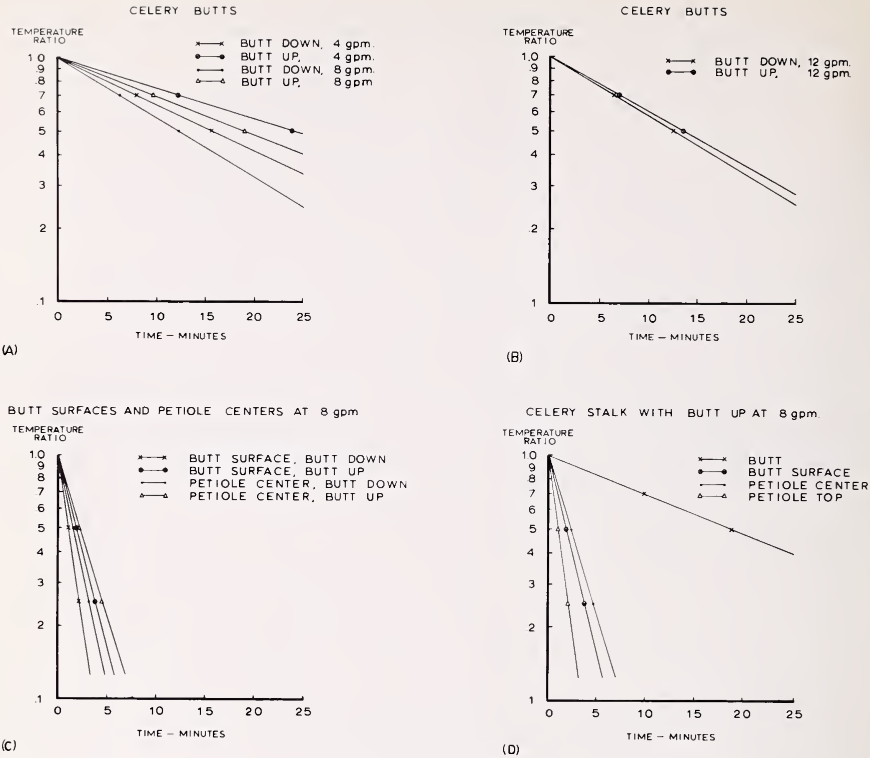

Figure 15.--Cooling curves for single stalks of celery hydrocooled in the laboratory cooler.

fast as or even faster than petioles of the smaller stalks because of more void space between stalks and better waterflow over petiole surfaces on larger stalks.

Standard and modified crates.--Half-cooling times for the test with standard and modified crates (the fourth test) do not indicate a significant decrease in half-cooling time for modified compared with standard crates (table 6). Half-cooling times for celery butts and for celery hearts were nearly the same in both cases. However, the half-cooling time for celery petioles that were packed in the modified crate was greatly reduced. This significantly reduced half-cooling time for celery petioles is a reflection of better flow of refrigerated water over the surface of the celery and through the crate.

Feasibility of Hydrocooling Unit Loads of Celery

Celery in stacked crates in the pilot plant hydrocooling room was cooled from 75° F. to 47.2° F. in 35.4 minutes at a waterflow rate of 63.2 g.p.m. This time compares favorably with 29.6 minutes, the time to cool celery to the same temperature in present types of flood-type hydrocoolers.

Table 5.--Hydrocooling 4 sizes of celery packed in wiremesh baskets, laboratory tests: Half-cooling times of butts, hearts, and petioles at 6 g.p.m. waterflow rate

Stalk part and orientation of stalk in basket[1]	Size 2	Size 3	Size 4	Size 6
	Minutes	Minutes	Minutes	Minutes
Butt:[2]				
Butt down....................	10.0	11.7	10.5	5.1
Butt up......................	17.0	15.4	12.0	8.9
Heart:[3]				
Butt down....................	2.2	1.1	1.7	1.9
Butt up......................	62.6	31.1	15.6	15.3
Butt surface:[4]				
Butt down....................	2.5	4.1	1.8	1.1
Butt up......................	1.9	1.7	3.8	1.5
Petiole surface:[4]				
Butt up......................	2.8	2.2	3.8	3.2

[1] 12 size 2, 20 size 3, 25 size 4, or 36 size 6 stalks were packed in a 12- by 12- by 10-inch wiremesh basket.
[2] Thermocouple inserted 1 inch deep into base of stalk.
[3] Thermocouple inserted 2-1/2 inches deep into base of stalk.
[4] Thermocouple on outer surface of stalk 1 inch from base and 7-1/2 inches from base of stalk for butt and petiole respectively.

Table 6.--Hydrocooling celery packed in standard and modified wirebound crates, laboratory tests: Half-cooling times of butts, hearts, and petioles at 6 g.p.m. waterflow rate

Stalk part, orientation of stalk in crate, and thermocouple number (fig. 13)	Standard crate	Modified crate
	Minutes	Minutes
Butt, butt down:[1]		
2..................................	8.3	8.9
8..................................	8.1	11.0
Heart, butt up:[2]		
6..................................	30.0	33.9
7..................................	66.6	--
Petiole:[3]		
Butt up, 3.........................	12.6	1.9
Butt down, 4.......................	12.8	2.9
Butt up, 5.........................	9.5	2.6

[1] Thermocouple inserted 1 inch deep into base of stalk.
[2] Thermocouple inserted 2-1/2 inches deep into base of stalk.
[3] Thermocouple just below petiole surface, 7-1/2 inches from base of stalk.

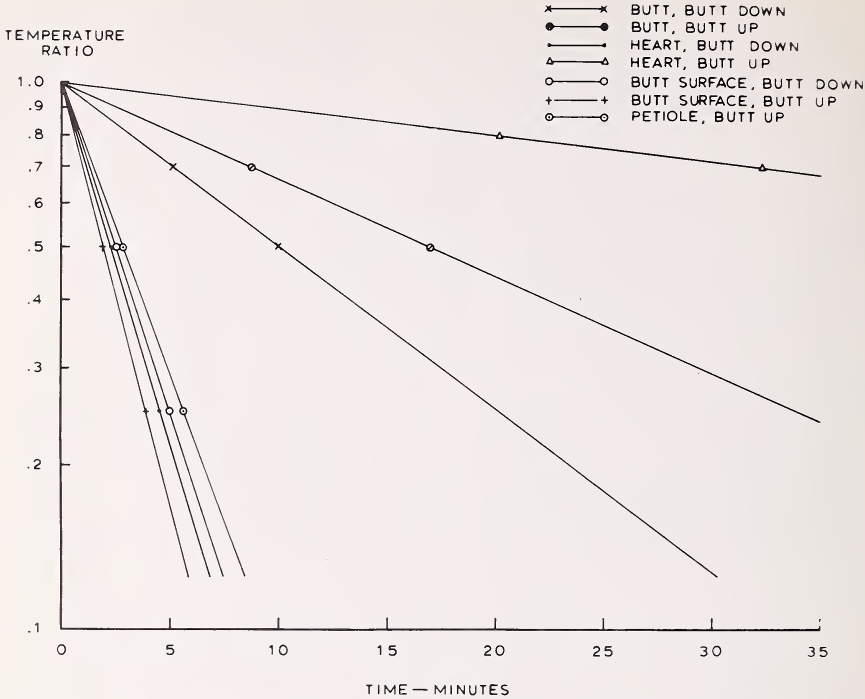

Figure 16.--Cooling curves for size 2 celery packed in a wiremesh basket and cooled with 6 gallons of water per minute.

The time to cool different layers of crated celery from 75° F. to 47.2° F. with 38° F. refrigerated water can be calculated by doubling the half-cooling times shown in table 1. The layer which has the longest half-cooling time should be used to determine the hydrocooling time for the complete stack.

If refrigerated water can be held to a temperature of 35° F., celery temperature at the end of two half-cooling times will be 45° F. (assuming 75° initial product temperature). Also, if the refrigerated water can be held to 35° F., celery temperature will be 47.2° F. in 30.0 minutes, compared with 35.4 minutes when the water temperature is 38° F.

For an example of how to calculate the cooling time required for a specific product temperature, see the calculation in the appendix.

As previously noted in discussion of results of hydrocooling celery, 2,237 gallons of 38° F. refrigerated water sprayed at the rate of 63.2 g.p.m. will be needed to cool celery from 75° F. to 47.2° F. In pilot plant tests, a total of 4,049 gallons of 38° water 91.2 g.p.m. per stack was needed to cool celery from 75° F. to 47.2° F. Although the gallonage of water sprayed onto the stack was nearly doubled, the cooling time was not decreased. This may have been caused by inefficiencies in the nozzle arrangment used in the cooling tests. Also, the narrow opening between crate slats restricted the amount of water which could pass through the top crate and thus the amount available to cool celery packed in lower crates in the stack.

The pilot plant test using modified celery crates (modified to enlarge the opening between the veneer slats) indicated that if slat widths were reduced by 3/4 inch, the hydrocooling of celery packed in wirebound crates would be improved. Although a similar test conducted in the laboratory did not indicate the same results, the laboratory test was not replicated and the results obtained in the pilot plant should be more indicative of possible improvement in cooling times with modified celery crates.

In pilot plant tests, butts of celery stalks packed in the top crate of unit loads cooled equally as fast as similar size stalks packed in a wiremesh basket and cooled in controlled laboratory conditions. Moreover, cooling achieved in the second and third layers of the stack at the 63.2 g.p.m. flow rate (4 g.p.m. per square foot) compares favorably with cooling of similar stalks in the laboratory at 6 g.p.m. per square foot.

As seen in table 4, the hearts of large stalks tend to cool very slowly when stalks are packed butt up. This decrease in cooling rate is not as pronounced in the single stalks (table 3), but still points out the effect of stalk orientation in the packed crate. Celery hearts packed butt down will cool much faster than those packed butt up. Also, the effect of size is readily apparent in tables 3 and 4. As size increases, the cooling time also increases.

These effects may be used to advantage especially for celery sizes 2-1/2 and 3, which are packed in wirebound crates in five layers. If the crate were positioned during cooling so that three layers of stalks within the crate were oriented butt down, more heat could be removed from the stalks in the crate during a given period.

CORN

Pilot Plant Studies

Test Procedures

Two tests with sweet corn were made to evaluate the performance of the stack hydrocooling system, and two tests were made to compare stack cooling with bulk cooling and with the present system of cooling. Waterflow rates were the same as those used in the pilot plant celery tests, and the water temperature was 35° to 38° F. The temperature of the corn at the beginning of each cooling test was approximately 90° F.

Corn crates were stacked in the pilot plant hydrocooling room 40 crates to a stack (five layers high, eight crates per layer). A corn stack was 66 inches high and weighed approximately 1,680 pounds (fig. 17). The wirebound corn crates were 24 by 12 by 11 inches. In the stack hydrocooling tests, the 12-inch dimension of the crate was vertical; in this position, the corn ears are also vertical.

In the first test of stack hydrocooling, thermocouples were inserted into corn kernels and into the center of the cob, 2 inches from the base of the cob. Kernel temperatures were measured in the top and bottom crates of the 5-layer stacks. Cob temperatures were measured in crates in each of the five layers.

In the second test, thermocouples were placed in a bottom-layer crate, in a third-layer crate, and in a top-layer crate. Thermocouples in each crate were placed in the center of the cob, in the outer shuck, and in the corn kernel. Thermocouples in the center of the cob were 2 inches from the end of the cob. Thermocouples in the outer shuck measured the temperature of the outer leaf of the shuck. The third thermocouple measured temperature at the base of the kernel.

In the third test, designed to compare stack cooling with bulk cooling, corn from 12 crates (720 ears) was unpacked and jumble-piled into a pallet box 47 by 47 inches and 30 inches deep. Center cob, outer shuck, and kernel temperatures were measured on three ears of corn. One ear was placed at the top of the pile, one in the center of the pile, and one at the bottom of the 24-inch-deep pile of corn.

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Figure 17.--Block pattern stack of corn crates in pilot plant hydrocooler.

The fourth test was made to compare the performance of stack and conventional flood-type hydrocooling systems. Center-of-cob and kernel temperatures in two crates in a conventional hydrocooler were recorded. The thermocouple in the center of the cob was 2 inches from the end of the cob and the thermocouple in the kernel was at the base of the kernel.

Temperature was measured by copper-constantan thermocouple junctions and was manually read and recorded from a potentiometer at 3-minute intervals.

Cooling coefficient values for cobs packed in crates were calculated and averaged for the cooling time period of 15 to 60 minutes. Cooling coefficients for kernels were averaged for the time period of 10 to 60 minutes.

In the test to evaluate cooling rate for corn piled in a pallet box, cooling coefficients for cobs were averaged over a 15- to 60-minute time period. Cooling coefficients for kernels and shucks were averaged from the beginning of the cooling cycle until 40 minutes after the test began.

Results of the corn cooling tests in this section of the report are given in the tables in terms of the half-cooling time previously defined. (See example in appendix for procedure to convert cooling coefficient to half-cooling time.)

Results

Unit loads.--Cooling curves for corn packed in crates and stacked in unit loads of 40 crates are shown in figure 18.

Corn stacked in unit loads of 40 crates cooled very slowly at all three waterflow rates (table 7). Half-cooling time for ears of sweet corn sprayed with 35.5 gallons of refrigerated water per minute ranged from 41 to 132 minutes. The bottom layers of the stack cooled very slowly at the low waterflow rate. Half-cooling times were considerably less at 63.2 g.p.m. waterflow than at 35.5 g.p.m. Further improvement was also apparent when 91.2 gallons of refrigerated water per minute was sprayed onto the stack. However, corn in the bottom crate

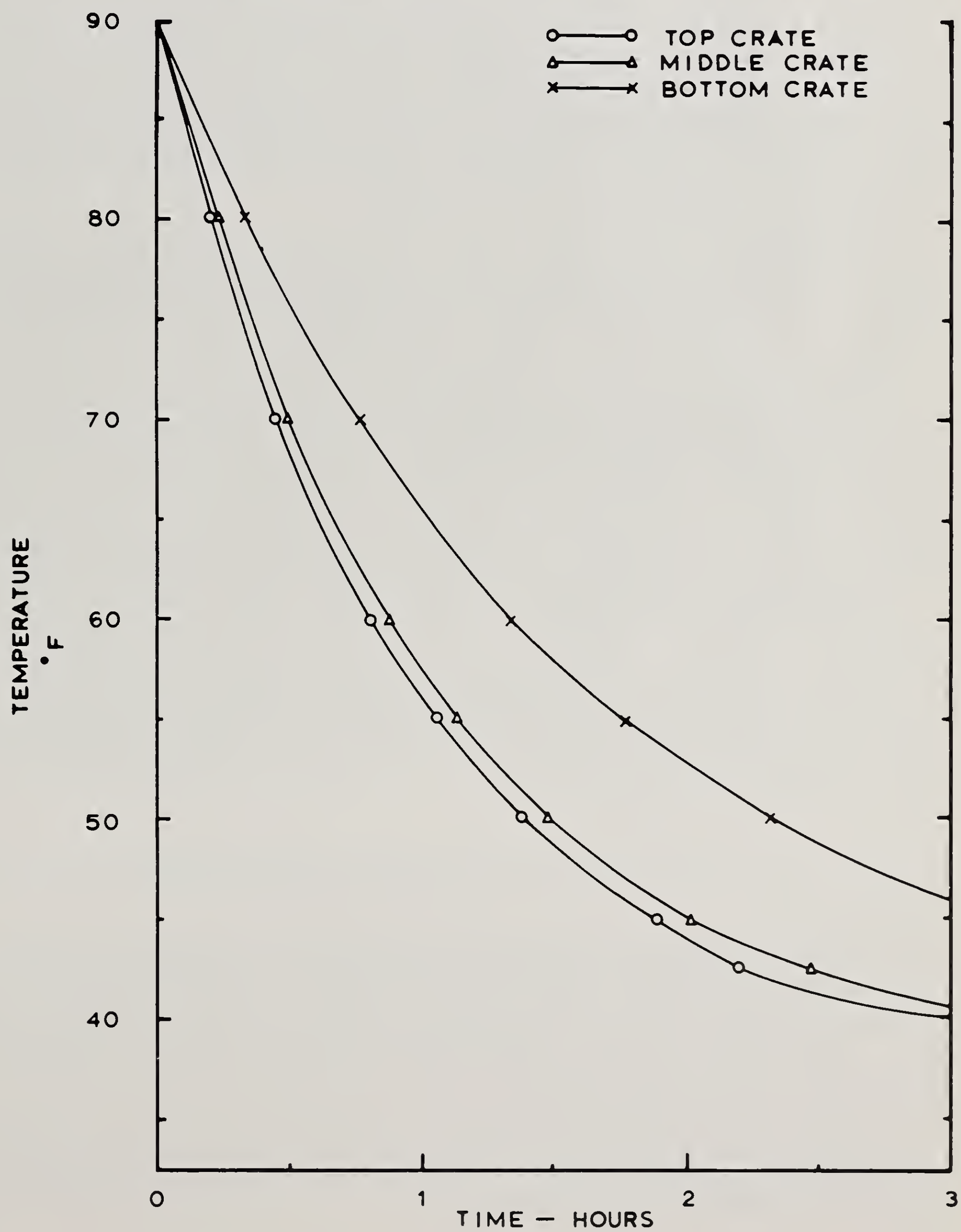

Figure 18.--Cooling curves (based on cob temperature) for ears of corn packed in crates in the top, middle, and bottom layers of a stack five crates high, sprayed with water at 91.2 g.p.m.

Table 7.--Hydrocooling sweet corn packed in wirebound crates and stacked in unit loads of 40 crates, pilot plant tests: Half-cooling times of cobs at three waterflow rates[1]

Location of corn in 5-high stack of crates	35.5 g.p.m.	63.2 g.p.m.	91.2 g.p.m.
	Minutes	Minutes	Minutes
Top crate	73.1	51.6	39.0
4th crate	40.6	34.8	46.5
3d crate	94.5	43.0	42.1
2d crate	131.6	56.9	44.9
Bottom crate	82.3	69.8	66.2

[1] Thermocouples inserted to center of cob 2 inches from base of cob. Half-cooling times for ears in center row in the crates (3d layer of corn when packed) are shown. Half-cooling times for ears in the intermediate row in the crates (2d layer of corn when packed) were similar.

of the stack that was sprayed with 91.2 gallons of 38° F. water per minute needed 66.2 minutes to complete the first half-cooling period--the time required to cool corn in the stack from 90° to 64° F. Under these conditions, corn temperature will be 51° F. at the end of the second half-cooling period and 44.5° F. at the end of the third half-cooling period. If three half-cooling time periods are needed to reduce corn to a sufficiently low temperature for shipping, stack precooling will require more than 3 hours.

Pallet box.--To determine whether the same precooling facilities designed to precool unit loads of stacked celery crates can be used to cool sweet corn, one further test with this equipment was conducted. In the test, 12 crates of corn or 720 ears were piled into a pallet box. This box was set under a water nozzle and the temperature of the corn was recorded during hydrocooling.

Half-cooling time for corn piled in the pallet box is shown in table 8. Cob temperature at the bottom of the pile was reduced from 90° to 64° F. at the end of 29 minutes. Three half-cooling periods, needed to reduce corn temperature from 90° to 44.5° F., totaled 87 minutes when 63.2 g.p.m. of refrigerated water was sprayed into the box. However, not all of the water sprayed from the nozzle was directed into the pallet box. Improvement in water distribution should increase the cooling coefficient and decrease the time to cool corn.

Conventional hydrocooling.--Half-cooling times shown in table 9 are for corn packed in wirebound crates and cooled in a conventional flood-type hydrocooler. In conventional hydrocoolers, the crates are tipped up, so that during hydrocooling, the ears of corn are vertical, in five rows (layers when packed). The half-cooling time varied from 18 to 28 minutes depending upon the layer in the crate in which corn was packed. In the conventional hydrocooler, a total time of approximately 80 minutes for three half-cooling periods is needed to reduce corn temperatures from 90° to 44.5° F.

Laboratory Studies

Test Procedures

Tests to measure heat transfer characteristics of sweet corn were carried out in a thoroughly agitated cold water bath. Five runs were made with a test specimen that consisted of a portion of the whole ear to simulate a cylinder whose length is equal to its diameter. These ear ends were sealed with Testors[6] model cement. Three runs were made with specimens whose lengths were greater than their diameter. Their ends were thermally insulated.

[6] Trade names are used in this publication solely for the purpose of providing specific information. Mention of commercially manufactured products does not imply endorsement by the Department of Agriculture over similar products not mentioned.

Table 8.--Hydrocooling sweet corn piled in a pallet box, pilot plant tests: Half-cooling times for cobs, kernels, and shucks, two waterflow rates

Location of ear in pallet box and location of thermocouple in ear[1]	63.2 g.p.m.	91.2 g.p.m.
	Minutes	Minutes
Top of pile:		
Cob	25.5	28.2
Kernel	14.0	16.1
Shuck	5.6	3.5
Center of pile:		
Cob	--	55.2
Kernel	26.7	21.8
Shuck	8.6	12.9
Bottom of pile:		
Cob	29.1	34.2
Kernel	26.9	21.0
Shuck	6.6	6.0

[1] The pallet box was 47 by 47 by 30 inches; the corn was piled 24 inches high. Thermocouples were inserted 2 inches from base of cob to center of cob, to the base of kernel, and to just below the outer surface of shuck.

Table 9.--Hydrocooling sweet corn packed in wirebound crates in conventional hydrocooler: Half-cooling times of cobs and kernels

Ear part and location of ear in crate[1]	Half-cooling time
	Minutes
Cob:	
3d layer	18.5
2d layer	28.1
Kernel, 2d layer	14.5

[1] Thermocouples inserted 2 inches from base of cob to center of cob and to the base of kernel.

Temperature was measured on the ear surface, at the ear center, and at 1/8-inch intervals along the radius from the center to the surface. Copper-constantan (36 A.W.G. wire) thermocouples were used.

Diameter of the cob, thickness of kernel and husk, and outside diameter of the ear were measured. Dimensions were practically standard for all specimens. The cob radius was 1/2 inch, the kernel was 3/8-inch thick, and the husk was 1/8-inch thick. Total outside diameter of the ear was 2 inches in each case.

Results

A heat property called "effective" thermal diffusivity can be determined when cooling time and ear size are known. Thermal diffusivity is a thermal property that describes the heat transfer characteristic of a substance during transient heating or cooling. The term "effective" thermal diffusivity is used here because the characteristic shape and anatomy of corn fail to conform precisely to stipulated conditions of symmetry and homogeneity for thermal diffusivity. "Effective" thermal diffusivity is a valuable aid in establishing cooling rate criteria. Values reported by run in table 10 represent the average of 12 to 15 individual computations made at 4-minute intervals extending over a cooling cycle of 45 to 60 minutes.

The unexplainable deviation between runs, which resulted in high coefficients of variation, is more likely attributable to experimental error than to characteristics of the material. However, there does appear to be some correlation between effective thermal diffusivity and density. Because of the large variation, it is perhaps useless to attempt to show a statistical difference between the two methods tested (length equal to diameter vs. length greater than diameter). By observation, there appears to be little difference; hence all runs were arbitrarily averaged to obtain one value. This value was used to prepare the curves of figure 19. The data in tables 11 and 12 in the appendix provide the basis for the computations.

The question of where to measure the temperature of hydrocooled sweet corn has long baffled some experimenters and many shippers. Obviously the cob center provides one logical choice. At any time during or immediately following hydrocooling, the temperature is highest at the center of the cob. Also, cob temperature provides a convenient relative measure for comparing cooling effectiveness. However, cob temperature does not provide a realistic measure of the amount of heat extracted during a cooling process.

On the assumption that an ear of corn is a homogeneous cylinder, the temperature that would occur at a point that divides the mass may be predicted. This point is approximately 0.7 the distance along the radius from the center to the surface. In this report it is called the mass center.

Actually, an ear of sweet corn is not a homogeneous cylinder, but is comprised of layers of concentric cylindrical shells around a pith core. A typical ear of sweet corn has an overall

Table 10.--"Effective" thermal diffusivity, density, and thermal conductivity of sweet corn of the Golden Bantam variety

Shape of test specimen and run number	Diffusivity	Density	Conductivity
	Sq. ft./hr.	Lb./cu. ft.	B.t.u./hr. ft. °F.
Length equal to diameter:			
Run 1	0.00446	54.7	0.195
Run 2	.00418	50.6	.169
Run 3	.00354	51.4	.146
Run 4	.00406	51.7	.168
Run 5	.00383	49.5	.152
Average, runs 1-5	[1] .00401	51.6	.166
Length greater than diameter, ends insulated:			
Run 6	.00411	50.0	.164
Run 7	.00360	49.4	.142
Run 8	.00355	51.1	.145
Average, runs 6-8	[2] .00375	50.2	.150
Average, all runs	.00388	50.9	.158

[1] Coefficient of variation = 27.5 percent.
[2] Coefficient of variation = 26.1 percent.

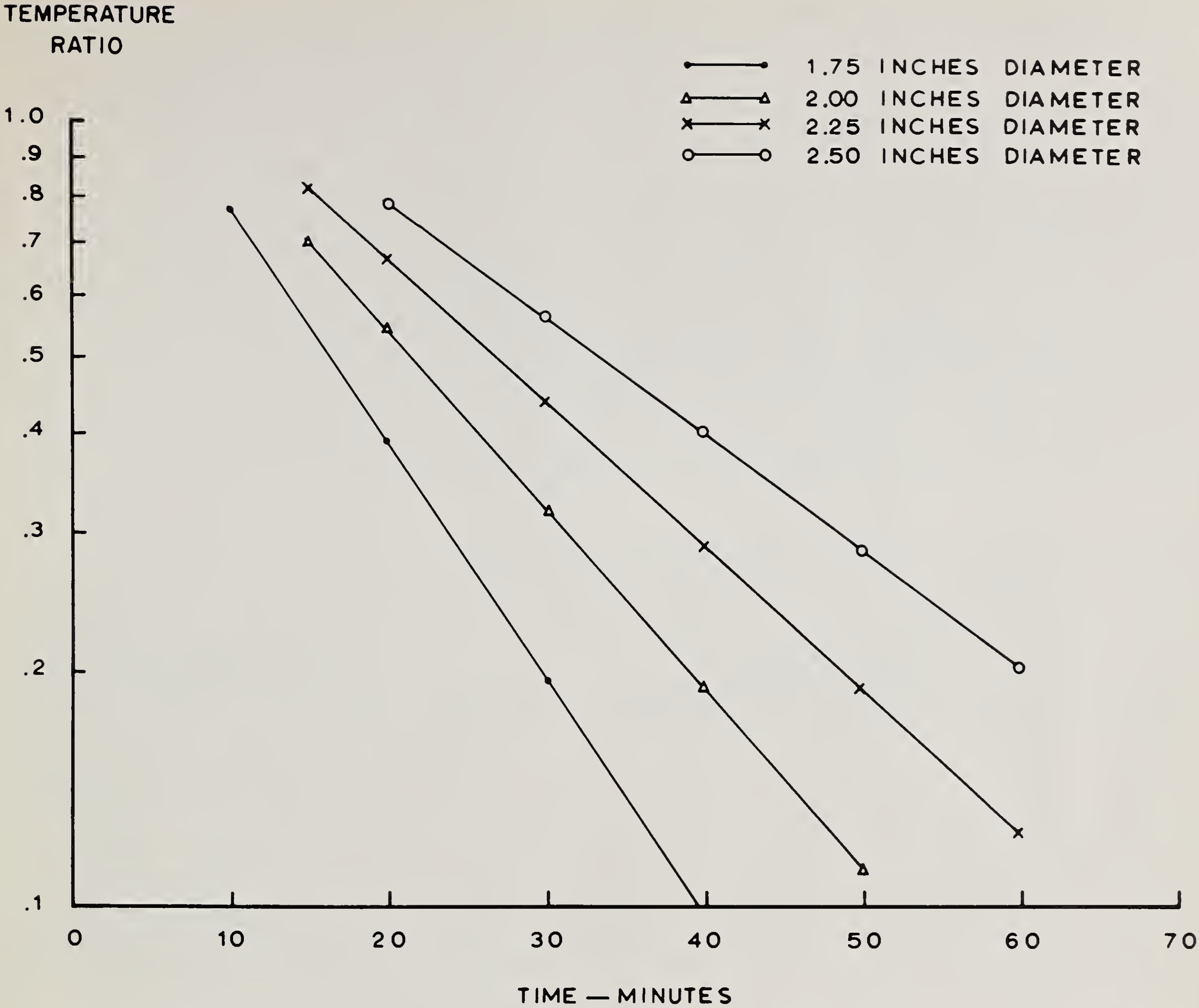

Figure 19.--Characteristic cooling curves for ideal cooling rate of specified corn ear sizes with temperature measured at the center of the cob along both axes.

diameter of 2 inches. The thickness of each constituency along the radius is 1/2 inch for the cob, 3/8 inch for the kernel layer and 1/8 inch for the husk. On this basis, and assuming reasonably comparable density, the husk and the kernel comprise the major mass constituency of the total ear.

On the basis of a homogeneous cylinder, the mass center occurs at a point approximately midway through the kernel layer. Temperature measured at this point would be more nearly indicative of the amount of heat extracted from or remaining in hydrocooled sweet corn than temperature measured at the cob center.

Figure 20 shows the temperature history, in terms of fractional temperature difference, for a 2-inch-diameter ear of sweet corn during ideal hydrocooling. Fractional temperature difference is the difference between the temperature at the mass center and cob center and that of the water, divided by the difference in the initial uniform temperature of the corn and that of the water. Ideal hydrocooling means that the ear surface is at the same temperature as the cooling water. The two curves provide a comparison between predicted temperatures at the cob center and at the mass center. Computations were based on the average "effective" thermal diffusivity given in table 10.

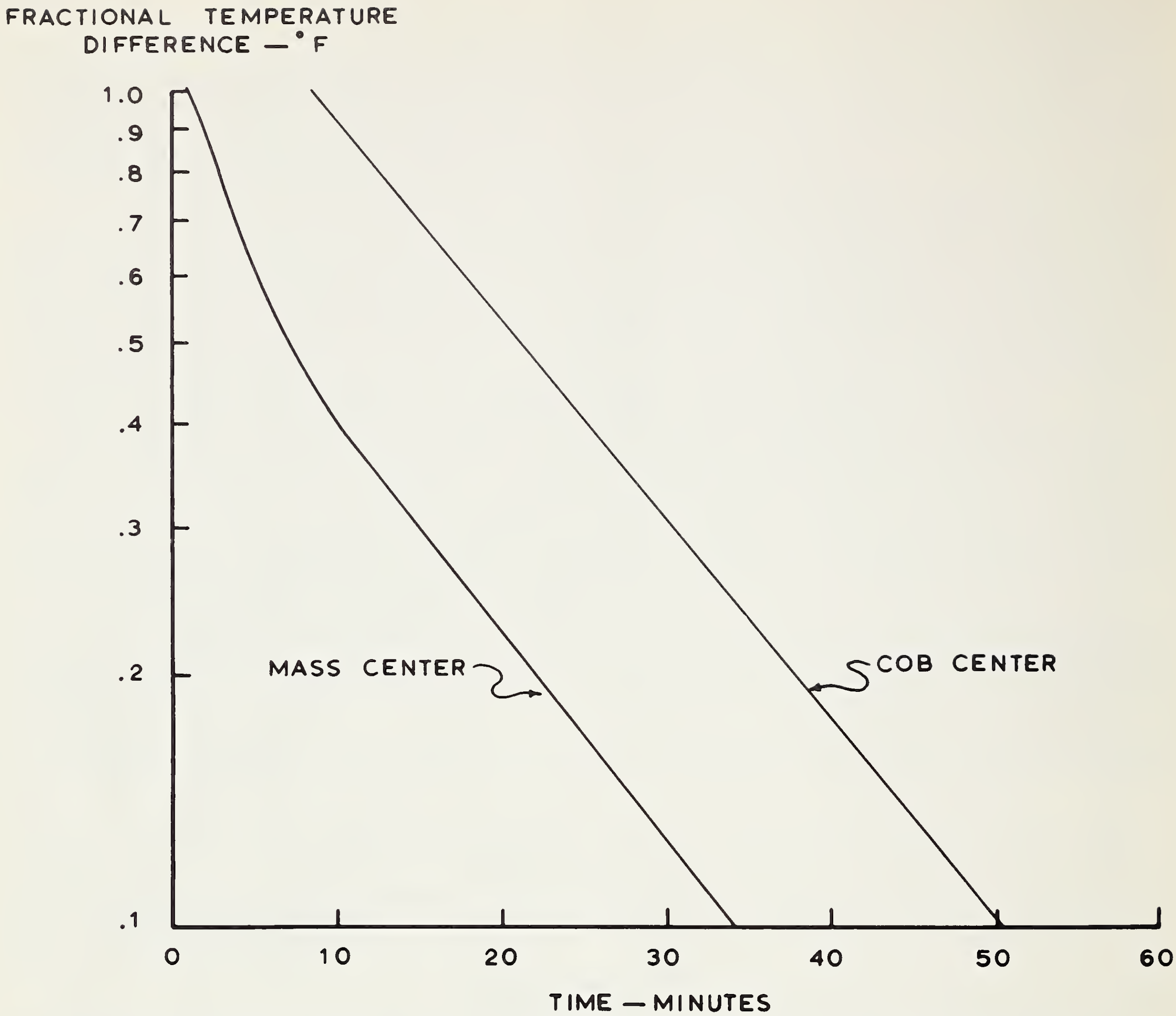

Figure 20.--Temperature history for a 2-inch-diameter ear of sweet corn during ideal hydrocooling.

Feasibility of Hydrocooling Unit Loads of Corn

To best preserve sweet corn quality, corn temperature should be less than 45° F. before the corn is loaded and shipped. Sweet corn that has an initial 90° F. temperature will be cooled by 38° F. water to 64° F. by the end of the first half-cooling period. At the end of the second half-cooling period the temperature will be 51° F., and at the end of the third half-cooling period it will be 44.5° F.

Corn cooled very slowly in stacked crates in the pilot plant hydrocooling room. At a waterflow rate of 91.2 g.p.m. corn temperatures (measured at the center of the cob) were reduced from 90° to 44.5° F. in 3-1/3 hours (table 7). At a waterflow rate of 63.2 g.p.m., 4-1/2 hours was needed to reduce corn to this temperature. If corn crates were stacked only four-high rather than five-high, only 2-1/2 hours at 91.2 g.p.m. would be required to cool corn to about 45° F.

These cooling times are rather slow compared with those obtained with the conventional flood-type hydrocooler. In the conventional cooler, approximately 1-1/3 hours are needed to reduce corn temperatures from 90° to 44.5° F. (table 9).

Thus, if precooling to 45° F. is desired before shipping, a method other than unit load hydrocooling of stacked crates of sweet corn should be used.

A look at the laboratory cooling curves for sweet corn may help at this point. The curve for 2-inch-diameter sweet corn (fig. 20) shows that 50 percent of the corn temperature reduction occurs in 22 minutes--in other words, one half-cooling time, Z, is equal to 22 minutes. Theoretically, 2Z should be 44 minutes, 3Z should be 66 minutes, etc. Actually, a more nearly correct value for 2Z is 35 minutes, and 3Z is 48 minutes (fig. 19.--temperature ratio equals 0.25 and 0.125, respectively). When we calculate a weighted average of the three values, we obtain a half-cooling time of 17.5 minutes. This approximates a solution by analytical computation based on Newtonian cooling coefficients.

Solutions of cooling problems presented in terms of half-cooling times are based on Newtonian cooling. This assumes that the logarithm of the temperature reduction is linear and temperature reduction at every point in the substance occurs simultaneously at an equal rate. It assumes, for example, that the temperature in the cob center of a sweet corn ear immersed in agitated ice water changes at the same rate and at the same time as that of the husk, or the kernel. This is not the case. Actually, there is a large time lag in temperature response at the cob center.

The presence of a time lag means that cooling rate data reported in terms of half-cooling times are not precise. Because the cooling coefficient is not constant, it is necessary to use a value that represents an average for some specified cooling time. A half-cooling time based on this average is likely to be too low during the early portion of the cooling period and too high during the latter portion.

The cooling curve (fig. 21) for crated 2-inch-diameter sweet corn immersed in agitated ice water reflects a cooling rate slightly less than the maximum attainable. However, it affords a

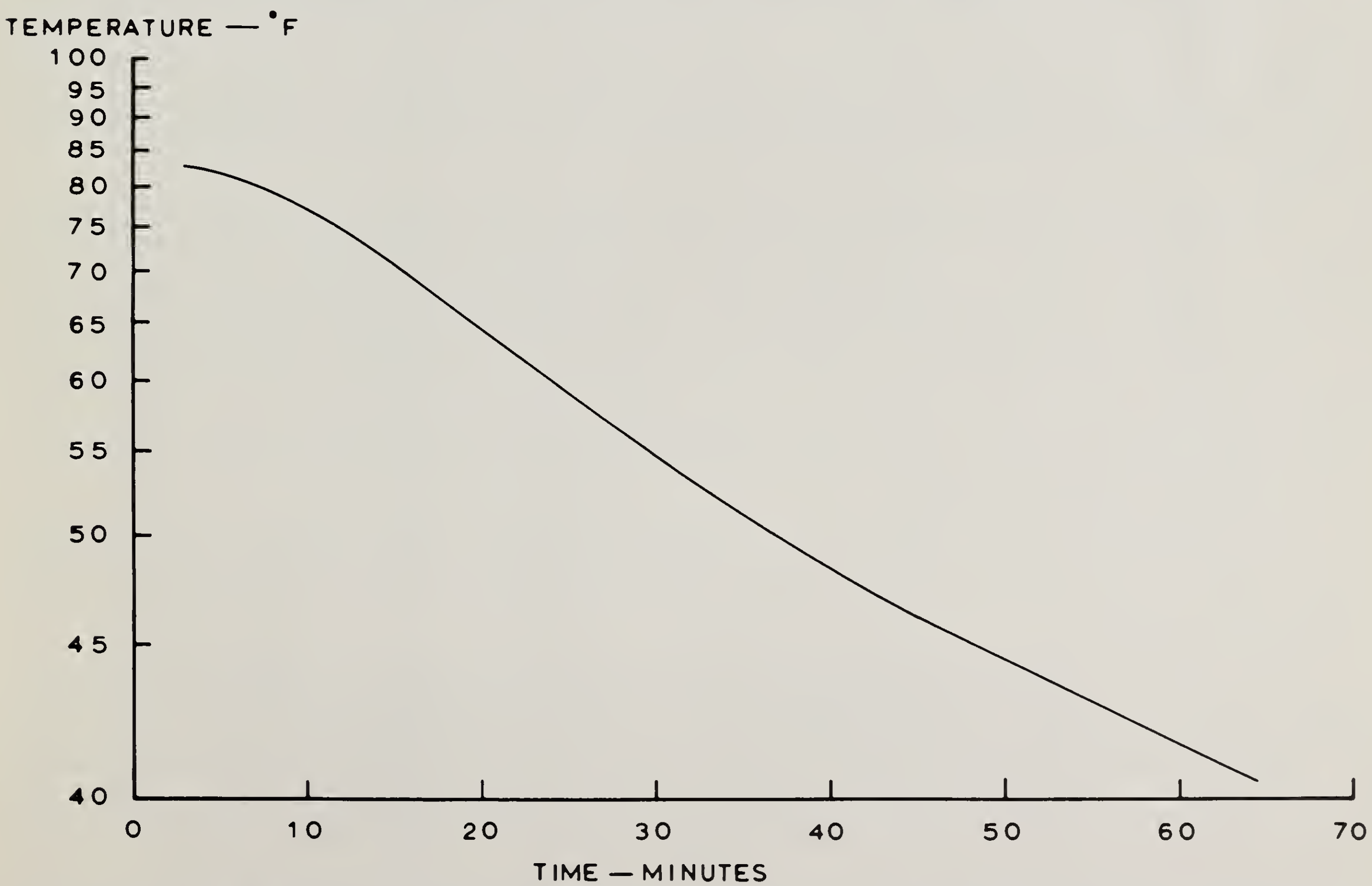

Figure 21.--Typical temperature response for cob center temperature of crated sweet corn immersed in agitated ice water.

desirable criterion for evaluating cooling rates of crated corn. The half-cooling time computed by the above described procedure is 20 minutes at the cob center.

Comparing the foregoing stated half-cooling times with the half-cooling times reported in table 8 affords a meaningful evaluation of cooling of corn piled into pallet boxes in the pilot plant cooler.

The half-cooling time for corn piled in the pallet box was 29 minutes. Further reduction of this time to nearly 20 minutes is possible by directing more water spray from the nozzles into the box.

Corn in a pallet box could be precooled to 45° in approximately 1 hour. This then could be the solution to the use of the same facilities to precool both celery and sweet corn.

Both from a quality and a volume standpoint (10,000 crates or more per day) a fast cooling system is necessary. Sweet corn sucrose level decreases at a rapid rate, especially at higher temperatures. As an example, after 16 hours at 86° F., half of the initial sucrose (based on 3.87 percent initial level) will be lost. Corn which has been immediately cooled to 50° F. will lose 50 percent of its initial sucrose in 72 hours, and corn which has been cooled to 32° F. will lose only approximately 21 to 22 percent of its initial sucrose by the end of 4 days.[7]

DESIGN OF A UNIT LOAD HYDROCOOLER

Floor Area and Room Layout

Two possible arrangements of aisles and stacks in a unit load hydrocooler are shown in figure 22. In floor plan A, stacks of crates are arranged in two blocks--each 8 rows wide and 16 deep (from front to back). Each stack is 5 layers high and contains 40 crates. There are two 11 1/2-foot-wide access aisles at the front and back of the rows. Along each side of the room, there are 7-foot aisles for traffic to move from the front of the building to the back. Stacks brought into the room from the front of the building are deposited in a 16-deep row and left in place for cooling. When the stacks are shipped, forklift trucks pick up the stacks from the railroad track side of the building and transport them to the railroad car or semitrailer truck for shipping.

Floor plan B is arranged with rows at right angles to aisles (fig. 22). Stacks of crates are brought from the field truck into the central 9 1/4-foot-wide aisleway. The fork truck driver makes a 90-degree turn into the 6-deep or into the 9-deep storage blocks. Stacks of crates are set under overhead shower nozzles and the fork truck returns to the field truck for another load.

With either layout, the room is loaded with stacks of crates brought in from the field truck with fork truck handling equipment. The fork truck driver sets the stacks under overhead shower nozzles, and when the row is complete, another worker turns on the water valve and the stack is cooled. When cooling is complete, the cooler worker turns off the water valve and the stack remains in place until it is shipped.

For loading out, a fork truck driver is dispatched from the shipping office to pick up stacks and transport them to the railroad car or semitrailer truck for loading. In floor plan A, access to the rows is from the 11 1/2-foot aisle, and in floor plan B, access to the rows is from the outside 8-foot aisles.

Improved floor space utilization can be obtained by using drive-through or drive-in rack storages. Rack storages are made from steel beams with horizontal components upon which the stacks rest, and vertical columns extending to the floor to support the horizontal beams. They are used to increase storage density. The drive-in racks are braced laterally in the center of the bay with the horizontal beams arranged at right angles to the aisle so they do not block access into the bay for materials handling equipment. The drive-through racks are tied to the

[7] Appleman, Charles O. and John M. Arthur. Carbohydrate Metabolism in Green Sweet Corn During Storage at Different Temperatures. Jour. Agr. Res., Vol. 17, pp. 137-152. 1919.

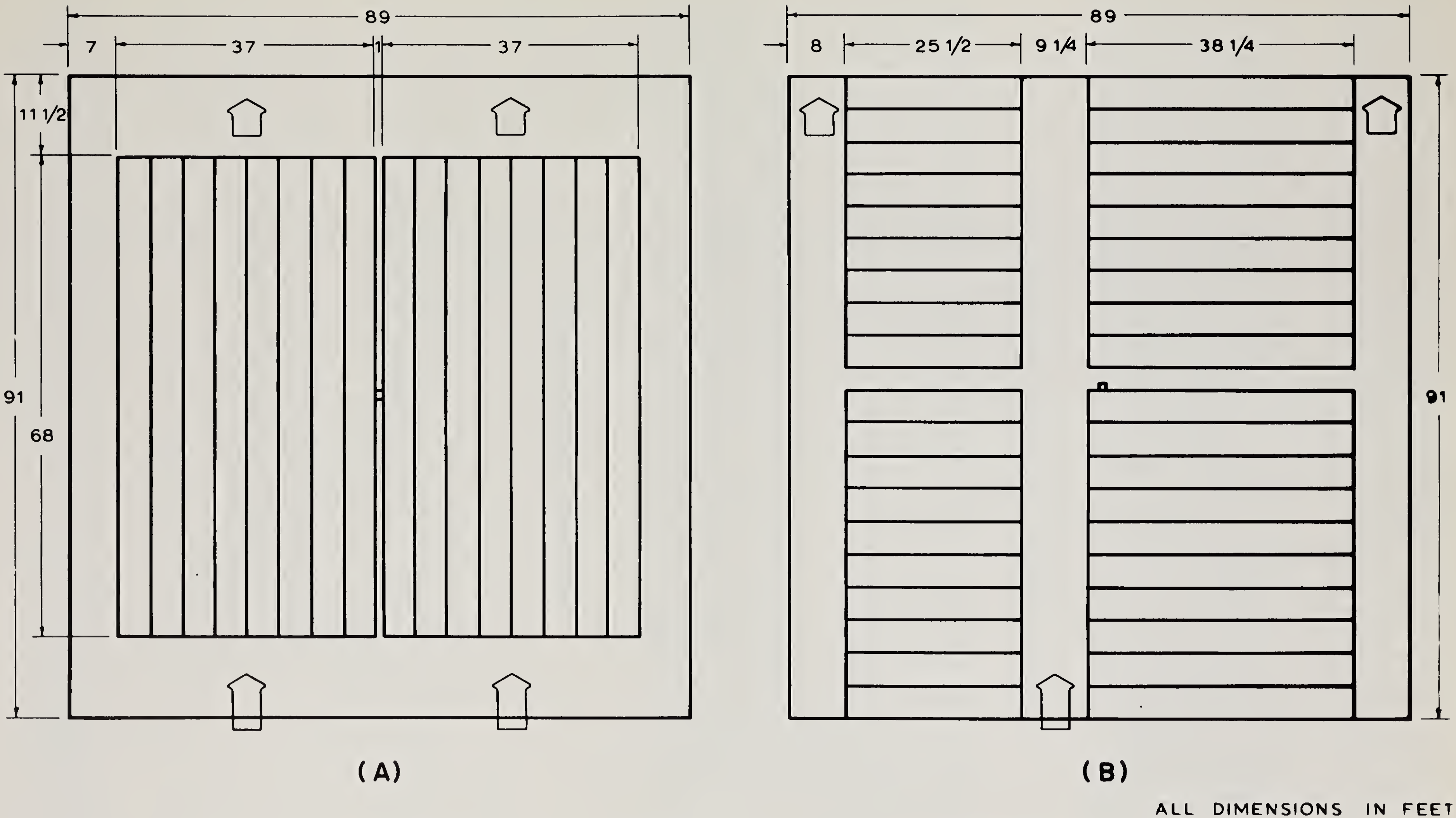

Figure 22.--Two arrangements of aisles and stacks in a unit load hydrocooler.

floor and ceiling, and permit handling equipment to move completely through the bay to the aisle on the other side. These storages can be two or three tiers high in the unit load hydrocooler.

A pallet 48 by 48 inches will be needed to hold the stacks of crates in rack storage. Floor space required for each stack is 51 by 55-1/2 inches, which allows space for supporting columns of storage racks, overhang of crates on pallets, and clearance between the load and rack structure.

In a storage area 89 by 91 feet, three aisles will be needed: one central and two side aisles (floor plan B). Eight hundred fifty-five pallets or 34,200 crates of celery can be stored and hydrocooled in place. Storage would be composed of 19 rows of 9-deep stacks and 19 rows of 6-deep stacks on either side of the central input aisle. The drive-through storage racks would be three tiers high. Total floor area will be 8,099 square feet. Storage of crate stacks in this area will use 5,602 square feet or about 70 percent of the total floor area. Aisles will use 2,298 square feet, and the remaining space will be lost to obstacles such as columns and walkways.

Water Nozzle and Pump Requirements

The spray nozzles used in the cooler should give uniform water distribution throughout a full-cone spray pattern. Waterflow capacity of approximately 80 gallons of water per minute for each stack of crates will be needed. A full-cone nozzle with 2-inch pipe connection and 15/16-inch orifice diameter will spray 59 g.p.m. at 10 p.s.i. and 82 g.p.m. at 20 p.s.i. A larger nozzle with 2-1/2-inch pipe connection and 1-1/8-inch orifice diameter will spray 83 g.p.m. at 10 p.s.i. and 115 g.p.m. at 20 p.s.i.

One spray nozzle should be installed 30 to 36 inches above each crate stack. If a storage rack is used, one nozzle should be installed at each tier level for each crate stack.

The nozzles should be arranged so that a water line is parallel to a row of stacks. When the water valve is turned on, water then will be sprayed from a complete row of nozzles.

The system should be capable of delivering at least 80 gallons of refrigerated water 32° to 35° F. per minute from each nozzle to be used at one time.

Handling Requirements

Palletized loads of crates can be picked up in the field by a hoist mounted on a truck or by forklift truck.

The worker on the field truck, operating hydraulic controls at the cab of the truck, manipulates the pickup attachment of the hoist under the pallet to pick up the load and set it on the bed of the truck. When eight pallet loads are accumulated on the field truck, the driver transports the loads to the precooling plant. At the plant, he unloads the crates onto a roller-conveyor dock, or other workers on forklift trucks unload them.

When the field truck is unloaded, the driver returns to the field for another load of crates.

Two workers with fork trucks move loads into the storage-precooling room. These workers set the crate stacks under a water nozzle to be cooled. A third worker can be assigned to help the fork truck drivers and to separate and restack celery sizes 6 and 8 into separate unitized loads. (These sizes should be stacked together in the field because only a small number are packed.)

Other workers needed at the precooling plant include an unloading and cooling supervisor, a cooler worker to turn water valves on and off for the hydrocooling system, and railroad car loading crews.

On the output end of the cooler, two loading crews are needed to load packed crates into railroad cars and semitrailer trucks. The crews each have one fork truck driver assigned to them to transport unitized loads of crates from storage to the dock.

APPENDIX

List of Symbols

Symbol	Quantity	Unit
Z	half-cooling time	hours
C	cooling coefficient	$^{\circ}$ F. per (hr.) ($^{\circ}$ F.)
F	temperature ratio	
θ	time	hours
t	temperature at any point in product	$^{\circ}$ F.
t_i	initial product temperature	$^{\circ}$ F.
t_o	temperature of water	$^{\circ}$ F.
t_c	temperature at center of product	$^{\circ}$ F.
t_s	temperature at surface	$^{\circ}$ F.
R	root of Bessel function	
J_1	Bessel function	
δ	thermal diffusivity	sq. ft. per hr.
r	radius of cylinder	ft.
ϕ	dimensionless number	
ρ	density	lb./cu. ft.
c_p	specific heat	B.t.u./lb. $^{\circ}$ F.
k	thermal conductivity	B.t.u./hr. ft. $^{\circ}$ F.

Formulas and Equations

The formula for half-cooling time is given by the equation:

$$Z = \frac{\log_e \frac{1}{2}}{C} \qquad \text{I}$$

The time needed to cool the produce to 1/2, 1/4, or 1/8 of its initial temperature is Z, $2Z$, or $3Z$, respectively. The temperature of the cooling medium must be constant for this equation to be applicable.

The cooling coefficient may also be used to compare the effectiveness of a cooling system. The equation is:

$$C = \frac{\log_e F}{\theta} = \frac{\log_e \frac{t - t_o}{t_i - t_o}}{\theta} \qquad \text{II}$$

The curves for figs. 14, 15, 16, 19, and 20 were prepared from data computed by the following equations:

$$\log_e F = C \qquad \text{III}$$

$$\text{and} \quad F = \frac{t - t_o}{t_i - t_o} \qquad \text{IV}$$

Half-cooling times shown in the tables can be converted to cooling coefficients by substitution in the equation:

$$C = \frac{\log_e \frac{1}{2}}{Z} \qquad \text{V}$$

Celery stalk temperature at any time during the cooling process can be obtained by substituting values for half-cooling time, celery temperature, and water temperature in equations V and II.

Examples of calculation when Z = 10 min., t_i = 75°, t_o = 38° F, θ = 15 min.:

$$C = \frac{\log_e \frac{1}{2}}{Z} = \frac{.693 \times 60}{10 \text{ minutes}} = 4.158 \qquad \text{V}$$

$$C = \frac{\log_e \frac{t - t_o}{t_i - t_o}}{\theta} \qquad \text{II}$$

$$\text{or} \quad \log_e \frac{t - 38}{75 - 38} = \frac{4.158 \times 15 \text{ minutes}}{60}$$

$$t = 51.1^\circ \text{ F.}$$

Thermal Diffusivity Tests on Sweet Corn

Application

Exact analytical heat flow solutions can be obtained with homogeneous inorganic materials such as common metals, ceramics, etc., whose physical and thermal properties are well known or can be measured precisely, and that may be accurately described as a cylinder, cube, or sphere. Biological materials, particularly fresh fruits and vegetables, do not conform precisely to these requirements. Sweet corn, for example, while shaped like a cylinder, is not a long cylindrical rod nor is it homogeneous. Also, values of physical and thermal properties must be taken as an average of the composite. They are sometimes referred to as apparent or effective values. Therefore, exact analytical solutions are not possible.

On the other hand, reliable predictions of the heat transfer of sweet corn under certain specified boundary conditions can be made provided the physical and thermal properties used in the analysis are the result of empirical tests. Such results contain built-in errors because of assumptions made during the course of the tests. These errors will correct themselves when the same assumptions are made, counterwise, to compute prediction equations.

Analytical Procedure

The expression for transient conduction heat flow from center to surface of an infinite cylinder (applied to a long cylindrical rod or a cylindrical rod whose ends are thermally insulated) which is initially at some uniform temperature and whose surface suddenly becomes changed to some different constant temperature, is given by the equation:

$$\frac{t_c - t_s}{t_i - t_s} = 2 \sum_{n=1}^{\infty} \frac{1}{R_n \; J_1 \; (R_n)} \quad e - \frac{R_n^2 \; \delta \; \theta}{r^2} = F \left(\frac{\delta \quad \theta}{r^2}\right)$$

By substituting ϕ for $\frac{\delta \quad \theta}{r^2}$ and expanding, the series may be written,

$$F(\phi) = 2 \left[\frac{e - R_1^2 \phi}{R_1 J_1 (R_1)} + \frac{e - R_2^2 \phi}{R_2 J_1 (R_2)} \ldots + \frac{e - R^2{}_{\infty} \; \phi}{R_{\infty} \; J_1 (R_{\infty})} \right]$$

$J_1 \; (R_n)$ is a Bessel function[8] of the n^{th} order and R_n is a root of the function. Tables of Bessel functions and roots are available in mathematics handbooks, as well as in some heat transfer and food engineering textbooks. Through the use of these tabulated values, solutions of F as a function of values of ϕ were computed.

The expression for a cylinder whose length is equal to its diameter is more involved and complicated than the one given for an infinite cylinder. For this reason, the expression is omitted from this discussion. However, for the reader's benefit, values of F as a function of ϕ for the cylinder whose length is equal to its diameter are listed in table 11.

Experimental Procedure

The effective thermal diffusivity and apparent density of the Golden Bantam variety sweet corn was measured. Diffusivity was computed from measured values of temperature recorded periodically after the corn was suddenly plunged into an agitated water bath at 35° F. Apparent density was measured by the volume displacement techniques.

Computed values of unaccomplished temperature change at periodic time intervals were equated to corresponding values of $\frac{\delta \quad \theta}{r^2}$ taken from table 11 for the 5 runs (length equal diameter) and from table 12 for the 3 runs (length greater than diameter). Effective thermal conductivity was computed by use of the equation:

$$k = \delta \rho c_p$$

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[8] Bessel functions have application in the solution of many practical engineering problems, among which, problems in heat transfer are prominent.

Table 11.--Temperature response at the center of a cylinder whose length equals its diameter after a sudden change from a uniform initial temperature to a surface temperature at some different but constant value

ϕ	F	ϕ	F
0.1200	0.7092	0.3100	0.1579
.1300	.6618	.3200	.1454
.1400	.6159	.3300	.1339
.1500	.5720	.3400	.1233
.1600	.5303	.3500	.1136
.1700	.4909	.3600	.1046
.1800	.4540	.3700	.0963
.1900	.4195	.3800	.0887
.2000	.3873	.3900	.0817
.2100	.3574	.4000	.0752
.2200	.3297-	.4100	.0692
.2300	.3040	.4200	.0638
.2400	.2807	.4300	.0587
.2500	.2583	.4400	.0541
.2600	.2380	.4500	.0498
.2700	.2193	.4600	.0458
.2800	.2020	.4700	.0422
.2900	.1681	.4800	.0389
.3000	.1714	.4900	.0358
		.5000	.0330

Table 12.--Temperature response at the center of a cylinder of infinite length after a sudden change from a uniform initial temperature to a surface temperature at some different but constant value

ϕ	F	ϕ	F
0.1200	0.7729	0.3100	0.2666
.1300	.7351	.3200	.2517
.1400	.6980	.3300	.2376
.1500	.6619	.3400	.2242
.1600	.6269	.3500	.2116
.1700	.5934	.3600	.1997
.1800	.5613	.3700	.1885
.1900	.5306	.3800	.1779
.2000	.5015	.3900	.1679
.2100	.4738	.4000	.1585
.2200	.4476	.4100	.1496
.2300	.4227	.4200	.1412
.2400	.3991	.4300	.1333
.2500	.3768	.4400	.1258
.2600	.3558	.4500	.1187
.2700	.3359	.4600	.1120
.2800	.3171	.4700	.1057
.2900	.2993	.4800	.0998
.3000	.2825	.4900	.0942
		.5000	.0889

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